Intelligent Electric Vehicle Integration - Domain Interfaces and Supporting Informatics

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Intelligent Electric Vehicle Integration - Domain Interfaces and Supporting Informatics

Abstract

This thesis seeks to apply the field of informatics to the intelligent integration of electric vehicles into the power system. The main goal is to release the potential of electric vehicles in relation to a reliable, economically efficient power system based on renewables.

To make intelligent EV integration a reality, it is prudent to understand the domain in its entirety. In this thesis, this is reflected by a thorough investigation of the stakeholders most relevant to the synergistic relationship between electric vehicle and grid.

The first investigation addresses the power market. The market can give system operators access to the flexibility of electric vehicles while at the same time creating an immediate economic incentive for the EV owner. A fleet operator is introduced to allow a fleet of electric vehicles to participate in the markets. Examples are provided on the specific markets and services in which the electric vehicle may be best suited to participate.

The next stakeholder investigated is the distribution system operator representing the low voltage grid. The challenge is assessed by considering a number of grid impacts studies. Next, a set of grid congestion mitigation strategies are proposed with a special attention to the impact that congestion would have on the operation of a fleet operator.

The third and most important stakeholder is the electric vehicle owner. The emphasis is on the plug in patterns of a number of Danish electric vehicle drivers. The objective is to understand how owner behavior will influence charging flexibility. It is indicated how plug in behavior may be predicted and how the resulting flexibility may be applied to achieve several different goals.
After having investigated the aims, constraints and requirements for the above stakeholders, the attention, in the second part of the thesis, is turned to three vital topics within the field of informatics.

The first topic is the control architecture that determines the placement and relationship between control systems used to control electric vehicle charging. A centralised market-based architecture is chosen and the functionalities needed by the control logic are defined.

The next informatics topic, communication, describes a set of protocols and standards applicable for electric vehicle integration. The study investigates the IEC 61850 standard and its ability to support smart charging.

Finally it is described how considerations to each of the stakeholders can be included in the optimization done by the fleet operator. It is shown how different markets can be considered and how stochastic optimization can be used to model uncertainty in regards to plug in behavior and grid congestion.

A large part of the above work have been done as contributions to the EDISON project in which the Thesis Author has participated. During the project the author has built a technical platform for testing several of the technologies mentioned above, against a small fleet of electric vehicles. This thesis is meant as an input for market players, system operators, fleet operators, fellow researchers and anyone with an interest in the role of the electric vehicle in the future power system.
Resumé

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I would like to start by paying tribute to the parties which have provided financial support to my PhD. The opportunity of pursuing a PhD and having the financial backup to explore the field through international conferences and external stays is a privilege not to be taken for granted.

I extend my heartfelt gratitude to my supervisors. To Bjarne, who originally introduced my to CEE and without whom I would not have written this thesis. To Jacob, whose dedication to the field and his center have been highly encouraging. To Dieter, whose passion for innovation is both contagious and inspirational. To Chresten who, while not an official supervisor, with his academic integrity and friendly nature has been a great support throughout these three years.

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Finally I thank my family, my caring parents and wonderful wife. Thanks for putting up with odd working hours and for politely listening to my lengthy rants about my research.

To all of you: THANK YOU.
The Limerick

Plug them in
Charge them up
From your own plug socket
Proudly put your foot down
As you drive around
In your electric rocket

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Glossary

A/S Ancient Service
CVPP Commercial Virtual Power Plant
DER Distributed Energy Resource
DSO Distribution System Operator
ENTSO European Network of Transmission System Operators for Electricity
EV Electric Vehicle
EVSE Electric Vehicle Supply Equipment
FDR Frequency controlled Disturbance Reserve
FNR Frequency controlled Normal operation Reserve
GAMS General Algebraic Modeling System
GVPP Generic Virtual Power Plant
ICE Internal Combustion Engine
ICT Information and communication technology
IEC International Electrotechnical Commission
OEM Original Equipment Manufacturer
PLC Power Line Communication
REST Representational State Transfer
RTO Regional Transmission Organization
SLA Service Level Agreement
SOA Service Oriented Architecture
SOAP Simple Object Access Protocol
SOC State-Of-Charge
TLS Transport Layer Security
TSO Transmission System Operator
TVPP Technical Virtual Power Plant
V2G Vehicle-To-Grid
VPP Virtual Power Plant
1

Introduction

1.1 EV Integration - Exploring a New Paradigm

Since Scottish inventor Robert Anderson built the first electric vehicle (EV) in 1832, the world has seen several attempts at electrifying the transportation sector. Successful EV introduction represents a challenge of daunting proportions but with an extraordinary potential for society. A challenge which can only be solved through a large set of disciplines spanning such fields as anthropology, politics, business, and technology.

In the following, the term “EV Integration” will be used to cover the technological challenges and describe the solutions that engineers and technicians working within electric components, power system design, informatics, and mathematics have to combine in a number of cross-disciplinary solutions. EV Integration research should, for instance, find solutions for:

- Infrastructure
- Roaming
- New EV services
- Smart grid integration

The goal of the latter area would be to minimize the adverse effects of introducing EVs as a new load in the power system and, instead, promote them as an active asset. This would ultimately reduce society’s cost, monetary as well as environmental, for the electrification of transportation. To achieve the above the EV itself would have
1. INTRODUCTION

to be equipped with capabilities so that it through information and communication
technology (ICT) can receive stimuli from its surrounding environment and through
logic adjust its charging or discharging behavior.

The main EV integration challenge addressed in this thesis is that of intelligent EV
integration into the power system as part of the smart grid concept.

1.1.1 The Smart Grid

The “smart grid” is said to be a trend of huge proportions in the Western world, a
significant revolution in the world of power and energy, a major paradigm shift in
markets, and one of the biggest engineering challenges of the century. It is, however,
also complex, early in its development and may have to be carried out in iterations as
part of an evolution.

The standard organisation “IEEE” gives the following definition: “The ”smart grid”
has come to describe a next-generation electrical power system typified by the increased
use of communications and information technology in the generation, delivery and con-
sumption of electrical energy.” [1]

Academia has put forward countless suggestions as to what this increased use of
ICT may be used for. Practical applications pursued at the moment include intelligent
metering, home automation, distributed production from Photovoltaics (PV), micro
combined heat and power units (CHP), and the control of loads such as air conditioning
(A/C), electric heating and EV charging.

The latter type of units, decentralized production and controllable loads, is often
grouped under the umbrella of a common term: distributed energy resources (DER).
DER is geographically distributed units with a resource potential. DER integration
constitutes a large part of smart grid research.

1.1.2 Distributed Energy Resources and Virtual Power Plants

As more DERs connect to the various levels of the power system, a new challenge for
the system operators - DSOs and TSOs - emerges. An interesting feature of DERs,
however, is that a sufficient degree of controllability and intelligence can elevate them
from being a challenge to the grid to, instead, being an asset. This raises the question
as to how and to what end DERs should be controlled. While the purposes typically
explored in academia relates to cost reduction, environmental and/or socio-economic,
it remains a question what purpose will bring about the greatest value. One answer to
the question as to how to coordinate the behavior of DERs, one viable solution is the
use of a Virtual Power plant (VPP)

A VPP describes an aggregated system in which many DERs are partly or fully
controlled by a single coordinating entity. For the individual DER, the VPP can hide
the complexity of market interactions and help meet market requirements that the
individual DER would be too small to accommodate. For the power system operators
and market players, the VPP aggregator could hide the complexity of interfacing with
a host of small individual units. The name “Virtual power plant” explicitly refers to a
VPP aggregator’s ability to mimic a traditional large power plant in behavior. VPPs
have been researched as part of the European FENIX project (2) and in academic
publications such as (3, 4).

When applied to EV integration the term “fleet operator” is often used for the
aggregating entity that controls the DERs as part of the VPP concept. This use of the
VPP concept can be found in the EDISON project and is described in a publication
co-authored by the Thesis Author (5). In this thesis both the term “fleet operator” and
“aggregator” will be used. A “fleet operator” can be said to describe the role taken by
a “real” actor operating in the current market and business space while “aggregator”
is closer to the more generic academic definition of the same entity. Currently, busi-
nesses in Denmark engaged in providing charging-related services to EV owners uses
terms such as “Electric Mobility Operator” to describe themselves. Chapter 5, “Control
architecture” will go into more detail with the structure of a VPP.

1.1.3 The Electric Vehicle and Utilization Concepts

While the EV is similar to other DERs according to the above definition, some of its
properties make it of particular interest. The main defining properties of an EV that
elevates it potential as a DER is that it is:

1. Expected to be grid-connected and available most of the time with a high degree
   of flexibility

2. A high-power, quick-response flexible load with an attached storage and possibly
   with bi-directional power flow capabilities
1. INTRODUCTION

For the first property the following can be observed. As other types of household attached DERs, such as CHP, Wind, and roof-installed solar, the unit is acquired and installed to meet a purpose separate from its potential functions in a smart grid context. For the EV this primary function is transportation which is also the main limiting factor in the degree to which the EV can be used for smart grid related matters. It has, however, been established that a typical vehicle is parked for as much as 23 hours a day in a publication by Kempton [10], and that these periods, especially at night, follow certain patterns that are predictable to an extent which allow EV charging to pursue other purposes than reaching a adequate energy level for the next drive. Kempton therefore describes the EV as “a vastly underutilized resource”.

The second property owes itself to the fact that the DER in question is built for transportation; i.e., it uses a drive train system capable of transferring large quantities of power to and from the battery on short notice. Generally speaking, it does not matter whether energy is transferred back and forth between the battery and motor due to acceleration and regenerative braking or between battery and grid as part of smart grid integration. It is also likely that batteries will become better at accommodating shallow mid-State-Of-Charge cycles. Having established the EV as a DER with a high grid potential, the remaining question is this: what should this potential be used for. In the remainder of this thesis the term “intelligent EV utilization concept” is meant to cover all services and goals that the manipulation of the direction, rate and timing of the power and energy exchanged between vehicle and power grid can accommodate.

The following introduces three EV capabilities that can each support a range of utilization concepts for various levels of the power system.

**Controlled charging** Charging is delayed or advanced in time based on, e.g., energy cost or renewable contents. A specific utilization concept could be following a dynamic energy tariff. Controlled charging is often described by the term “Smart charging”.

![Figure 1.1: Controlled charging](image)

*Figure 1.1: Controlled charging* - Illustrative example of controlled charging behavior
1.2 Quantifying the Benefits

**Active power services** Short-duration charging and, possibly, discharging operations. This capability can be used towards ancillary services - either the ones present in the current power market or new types of ancillary services aimed at the local distribution net.

![Figure 1.2: Active power service - Illustrative example of active power service behavior](image1)

**Energy backup** Using a portion of the EV battery capacity to store energy which is to be delivered back to the surrounding power system at a later point in time. This capability can be used towards the utilization concept of storing wind energy at hours with low demand.

![Figure 1.3: Energy backup - Illustrative example of energy backup behavior](image2)

The above types of behavior can be employed in either system-wide or local grid utilization concepts. Examples of the former is energy backup for transmission grid attached renewables and energy market prices. Local grid concepts could be voltage control, congestion mitigation, and co-existence with other DERs. This thesis will touch upon the above utilization concepts throughout this thesis.

1.2 Quantifying the Benefits

The benefits that the introduction of electric vehicles can accommodate can be divided up between immediate environment and health benefits and the additional socio-economic benefits that can be obtained through smart grid integration and EV intelligence.

1.2.1 Immediate Benefits to Environment and Health

On a local level, EV introduction will reduce particle emission and street noise. Both of these pollutants are proven to have adverse effects on the public health. Noise pollution
1. INTRODUCTION

have been investigated by WHO in [7] and particle pollution by Aarhus University in [8]. Besides from the intangible human consequences, the result is an increase in the cost of public health care and a decrease in workforce productivity.

On a national level the introduction of EVs can reduce oil dependency and greenhouse gas emission, respectively, thereby reducing human-made contributions to global warming. The latter is true not only when considering the pollution-free electric motor, but also when considering how the energy, on which it runs, was generated. The term “Well-To-Wheel” CO$_2$-emission encompasses the sum of produced CO$_2$ by all parts of the energy production chain.

Based on a Well-To-Wheel calculation, a typical EV would produce less than half the CO$_2$ than a traditional ICE car in the same size-class as seen in figure 1.4.

![Figure 1.4: CO$_2$ emission comparison](image)

**Figure 1.4: CO$_2$ emission comparison** - The EV emission is based on CO$_2$ production of energy generation in western Denmark (0.449 g CO$_2$/Wh), *data source: Dansk Elbil Komite [9]*

Electrifying the entire Danish transport sector would reduce the national CO$_2$ emission considerably. This means that the integration of EVs is crucial to meeting the milestones/targets of 2020, 2030 and 2050 for greenhouse gas emission issued by the Danish government.
1.3 Projects and Coordinated Work Efforts within EV Research

1.2.2 Benefits Achieved through Intelligent Integration

A unique feature of the EV is that it, after the point of acquisition, can become “cleaner” over time. This is true if the renewable component of a nation’s power generation increases over time and especially if the intelligence of the EV promotes and accelerates an increased penetration of renewable production.

The Danish TSO, EnergiNet.dk, have released a report on efficient use of wind energy [10] stating the following:

"The analysis shows that heat pumps and EVs have a big potential in creating a new and large flexible energy demand which mean that a larger portion of wind power can be used inside Denmark. Thereby Co2-emissions will be reduced considerably"

Another benefit related to intelligent EV integration is the socio-economic costs of implementing and operating a next-generation power system.

The general cost of the future power system has been investigated in another Energinet.dk report [11] which estimates a DKK 6.1 billion net-earning for Denmark if smart grids are implemented. The report stresses that the services provided by “green and flexible vehicles” are essential for realizing this potential. Energinet.dk report [10] even more explicitly mentions EV integration. From the report summary:

"It is furthermore of vital importance that solutions are developed that supports an intelligent interaction between electric vehicles, heat pumps and the power system..."

"...If this intelligence is not developed in the communication between power system and the new flexible demand, the socio-economic benefit of electric vehicle and heat pump integration will be reduced by approximately DKK 1.7 billion per year."

There is therefore good reason to promote the introduction of EVs in society and pursue an intelligent integration into the power system.

1.3 Projects and Coordinated Work Efforts within EV Research

Over the last couple of years, EV integration has received a lot of attention from both academia and industry. A lot of research groups have conducted and published research which is both relevant and valuable to EV integration. This section will mention some of the research groups and projects which have made significant contributions to the field.
1. INTRODUCTION

The EDISON project (12), “Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks”, was a research project whose goal it was to develop optimal solutions for EV integration, including network issues, market solutions, and optimal interaction between different energy technologies. The project has thoroughly investigated a long list of issues relating to EV introduction and integration.

The e-Mobility Berlin project have made significant contributions to the field (13). The project was initiated by Daimler AG (Mercedes-Benz) and the utility RWE. Among the participants are also battery, Electric Vehicle Supply Equipment (EVSE) and other auto-mobile original equipment manufacturers (OEM). The project introduced a fleet of 100 EVs supplied by Daimler and 500 EVSEs which were delivered and powered by RWE in the streets of Berlin for a large field test. The project was primarily aimed at developing and testing standardized solutions for electric vehicles and contributed towards infrastructure standardization in Europe.

The Vattenfall Wind-to-vehicle (W2V) project (14) was a cooperation initiative between BMW and the energy company Wattenfall. The project deserves mention for being among the first to demonstrate the ability of a group of EVs to participate in a system-wide utilization concept - charging based on wind production. For the demonstration, a complete ICT system was set up to coordinate a number of “mini-e” vehicles. The same group has moved on to do grid impact studies and to demonstrate that the coordination of EVs may also benefit the distribution grid.

The MERGE project (15) was launched as an “evaluation of the impacts that EV will have on the EU electric power systems regarding planning, operation and market functioning.”. Among the notable contributions of this project was its grid impact studies that in great detail, and for different topologies and EV integration levels showed the impact of EV introduction on European grids. The projects also defined a stage-based roadmap for the realisation of EV smart charging schemes, short and long-term.

A research group lead by Professor Willett Kempton, University of Delaware, has made great contributions to EV research (16). Among the contributions are the demonstration on market integration via Vehicle-To-Grid technology and the economic assessment of regulation power provision. Technically, the group has contributed with solutions in the form of control systems and power electronics for EV monitoring and
1.4 This PhD Study and its Contributions

control as well as communication solutions and the application of agent theory in the coordination of EV charging.

IBM researchers Carl Binding and Olle Sundstroem have worked on optimization methods to support smart charging. The researchers have considered a wide range of relevant parameters such as grid congestion issues, EV owner behavior, market trading, and battery lifetime issues. To this end they have used a equally long array of methods such as optimization (linear, quadratic etc.), grid modelling (load flow, network model etc.), battery models, and statistical techniques. The publications from these researchers constitute a great contribution to the field in general and have been an inspiration for parts of this thesis.

The International Electrotechnical Commission (IEC) have made standards relevant to EV integration, some of the most significant have been mentioned in several of the core publications of this thesis. The standards put forward by IEC can greatly influence the shape and direction of the field in Europe. The above is also true for the European Committee for Electro technical Standardization (CENELEC).

The above groups and projects has in several cases produced academic results which are useful as input to this thesis. These inputs will be described in the “related work” sections in each of the following chapters.

1.4 This PhD Study and its Contributions

This section outlines the exact goals of this study and the contributions made to address them. The objectives pursued by the Thesis Author are described in the “Thesis objectives and scope” section and the “Thesis documentation - content and structure” section describes the written contributions that documents how the PhD author have sought to meet the objectives. This is done by listing all the papers and book chapters that have been published and then map a chosen subset - the core publications - to the structure of this main thesis report.

1.4.1 Thesis Objectives and Scope

Solving any type of engineering challenge can be split into two basic steps: Firstly, a thorough investigation of the domain in which the challenge exist is done, and, sec-
1. INTRODUCTION

Finally, the best possible solutions are recommended. This basic, but very fundamental, approach allows for the definition of the two main objectives of this thesis:

1. To investigate the main stakeholders within intelligent EV integration and the objectives, considerations and constraints they each represent.

2. To identify and find the best contemporary informatics technologies to solve the challenge of intelligent EV integration.

By addressing the above objectives the main contribution of the thesis becomes an investigation of the domain in which the EVs will be integrated and the identification of appropriate informatics to carry out such an integration.

In the end, the thesis is meant to consolidate the EVs role in the ultimate, overarching mission of smart grid research: the development of a reliable, sustainable and economic power system.

This thesis divides the work done into two parts. The first part describes the domain investigation and the second deals with the investigated informatics solutions. Each part is described in the following sections.

1.4.1.1 Domain Interfaces

As more and more EVs connect to the power system, the foundation for relationships and dependencies to a new set of stakeholders is established.

Entities like fleet and system operators will have business models, objectives and constraints that may influence the charging behavior of an EV in many different ways. These new relationships should be implemented in a way that is financially beneficial, convenient and acceptable to the EV owner.

The domain considered in this thesis is grid-centric with a focus on three levels.

First there is the consumer-level representing the individual grid connection point. This level is included since understanding the behavioral patterns, value drivers and requirements of prosumers, in this case EV owners, is a clear necessity for EV integration. Next, the distribution level is included due to the very real operational challenges and opportunities that EV introduction may entail in this part of the system. Finally, on the system-wide level, the market is included to represent system-wide energy and...
power services since the market may drive the economic incentives behind the various intelligent EV utilization concepts.

The domain along with the levels described above is shown in figure 1.5.

**Figure 1.5: Domain overview** - Main stakeholders and objectives within intelligent EV integration

The stakeholders considered by this thesis, as part of the domain interfaces investigation becomes:

- Market player (Market integration)
- Distribution system operator (Grid integration)
- EV owner

Each of the above stakeholders is covered by a chapter in this thesis.

### 1.4.1.2 Supporting Informatics

Informatics, as part of computer science, covers the structure, algorithms, behavior, and interactions of natural and artificial systems that store, process, access, and communicate information. The thesis will apply part of the academic field of informatics to the specific application of EV integration.
The topics selected cover the major aspects of the information value chain: architectural system relationships between entities collecting and exchanging data; the ways in which the data is formatted and sent as part of the communication process between said entities; and, finally, the ultimate goal of predicting future events and achieve value through optimization.

The supporting informatics topics of this thesis becomes:

- System architecture
- Communication
- Optimization

Each of the above topics are covered by a chapter in this thesis.

This thesis and its publications have attempted to illuminate how the domain study of EV owner, grid and market integration have impacted recommendations within choice of technologies. The conclusions chapter will illustrate this relationship.

1.4.2 Thesis Documentation - Content and Structure

This main thesis document, made up by the following chapters and sections, is publication-based, i.e., this “enveloping document” lists and references a set of publication made throughout the PhD study and relies on them as a direct part of the thesis work documentation.

Each chapter have primarily been defined to cover a meaningful portion of the overall PhD thesis objectives, but will also be closely linked to one or more publications.

Since most of the documentation is left to the publications, the main objective of the following chapters will be to summarize findings, relate the work to that done by others, add possible corrections, supply more context and perspective, and finally to relate each topic to the field of intelligent EV integration in its entirety.

Two exceptions are chapter four “EV owner” and chapter seven “Optimization” where new material has been included which has not been documented elsewhere. The following sections will describe the contributions made by the author in terms of publications and project contributions, list a number of core publications with special relevance to the thesis and finally map them to the thesis structure.
1.4.2.1 Publication list

A subset of the publications by the Thesis Author has been selected as core publications. A core publication is a written contribution with special relevance to the objectives defined by the thesis. The letter next to the publication will be used as a identifier throughout the document.

**A**
Peter Bach Andersen, Junjie Hu, and Kai Heussen. 

**B**
Peter Bach Andersen, Rodrigo Garcia-Valle, and Willett Kempton. 

**C**
Peter Bach Andersen, Einar Bragi Hauksson, Anders Bro Pedersen, Dieter Gantenbein, Bernhard Jansen, Claus Amtrup Andersen, and Jacob Dall. 

**D**
Francesco Marra, Dario Sacchetti, Anders Bro Pedersen, Peter Bach Andersen, Chresten Træholt, and Esben Larsen. 

**E**
Andreas Aabrandt, Peter Bach Andersen, Anders Bro Pedersen, Shi You, Bjarne Poulsen, Niamh O’Connell, and Jacob Østergaard. 

**F**
Anders Bro Pedersen, Einar Bragi Hauksson, Peter Bach Andersen, Bjarne Poulsen, Chresten Træholt, and Dieter Gantenbein. 
**Facilitating a generic communication interface to distributed energy resources - Mapping IEC 61850 to RESTful Services.** *In Proc. First IEEE International Conference on Smart Grid Communications (SmartGridComm), (ISBN: 978-1-4244-6510-1), Gaithersburg , 2010.*
1. INTRODUCTION

The core publications are all publications to which the Thesis Author have contributed with a significant part of the work. An exception is the core publication D by Marra, which have been included since parts of the demonstrations described constitute proof-of-concept of work done by the author. All core publications are appended to this document. The Thesis Author have also made contributions to a number of other publications not directly included in or referenced by this thesis. They are not be included since the Thesis Authors role is smaller than in the core publication and/or the topic they address falls outside the scope of this thesis document. The following is the full list of publications to which the author have made contributions, excluding the core publications. (Begins on the following page...)
Anders Bro Pedersen, Peter Bach Andersen, Joachim Skov Johansen, David Rua, Jos Ruela, and Joo A. Peas Lopes.


Shi You, Junjie Hu, Anders Bro Pedersen, Peter Bach Andersen, Claus Nygaard Rasmussen, and Seung-Tae Cha.


Qiuwei Wu, Arne Hejde Nielsen, Jacob Østergaard, Seung-Tae Cha, Francesco Marra, and Peter Bach Andersen.


Carl Binding, Dieter Gantenbein, Bernhard Jansen, Olle Sundstroem, Peter Bach Andersen, Chresten Træholt, Francesco Marra, and Bjarne Poulsen.


Peter Bach Andersen, Bjarne Poulsen, Chresten Træholt, and Jacob Østergaard.


Morten Decker, Bjarne Poulsen, Peter Bach Andersen, Cresten Træholt, and Jacob Østergaard.


Peter Bach Andersen, Bjarne Poulsen, Morten Decker, Cresten Træholt, and Jacob Østergaard.

1. INTRODUCTION

Furthermore, the Thesis Author has made contributions to the following projects:

**EDISON** The Thesis Author has been in charge of DTUs participation in EDISON Work Package 3: “Distributed integration technology development” and has made written contributions to the technical reports of the project.

- (Internal report) Existing Asset Analysis.
- (Internal report) Distributed reference architecture.
- (Public report) D3.1 Distributed integration technology development.

The Thesis Author have developed large parts of the back-end system - The EDISON Virtual Power Plant (EVPP) - used for demonstrations throughout the project.

**SEESGEN ICT** The Thesis Author has contributed to the SEESGEN-ICT Work Package 4: “ICT for Demand Side Integration” Here the Thesis Author made written contributions to the reports:

- (Public report) D4-2: Report on ICT requirements, offers and needs for Demand Side Integration.

Having listed the previous contributions by the Thesis Author, the next section outlines this thesis document and its structure.

1.4.2.2 Thesis Structure

The structure of this document is made to reflect the two main objectives of the thesis. This means that the thesis consist of two parts: ”Domain interfaces” and ”Supporting informatics”. The ”Domain interfaces” part consists of chapters reflecting the key stakeholders identified and thus consists of chapters dealing with the EV owner, distribution grid and market. In the same way, the ”Supporting informatics” part holds three chapters covering control architecture, communications and optimization.

Each chapter will start with a list of the core publication that contribute to the specific topic.
1.4 This PhD Study and its Contributions

The thesis document structure, along with the publication to chapter mapping, is illustrated in figure: [1.6].

<table>
<thead>
<tr>
<th>Structure</th>
<th>Core publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART 1: Domain interfaces</td>
<td></td>
</tr>
<tr>
<td>Chapter 2 - Market integration</td>
<td>A,D,F</td>
</tr>
<tr>
<td>Chapter 3 - Grid integration</td>
<td>A</td>
</tr>
<tr>
<td>Chapter 4 - EV Owner</td>
<td>A,E</td>
</tr>
<tr>
<td>PART 2: Supporting informatics</td>
<td></td>
</tr>
<tr>
<td>Chapter 5 - System architecture</td>
<td>B,C,D</td>
</tr>
<tr>
<td>Chapter 6 - Communication</td>
<td>B,C,D</td>
</tr>
<tr>
<td>Chapter 7 - Optimization</td>
<td>E,F</td>
</tr>
</tbody>
</table>

**Figure 1.6: Thesis structure** - Thesis structure with core publications mapped to chapters

The thesis document will conclude with a “Conclusions” chapter that will present and discuss the results, make recommendations, and finally indicate areas in need of further investigation.
1. INTRODUCTION
## 2 Market Integration

This chapter deals with the market as part of the “Domain interfaces” investigations of this thesis. The following publications constitute the core contributions done by the Thesis Author to this area:

**B** A comparison of electric vehicle integration projects.

**D** Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves.

**E** Prediction and optimization methods for electric vehicle charging schedules in the EDISON project.

The publications will be referred to by their letter (B,D,E) in the following. Part of the material in this chapter, presented in the “Comparative study between ancillary service markets” section, is part of a special project report “Ancillary services and EV aggregator operation” done by the Thesis Author under supervision of Professor Willett Kempton at the University of Delaware. The report has not been published, but is available upon request.

### 2.1 Introduction

The existing power and energy markets may represent the easiest short-term way of integrating fleets of Electric Vehicles (EV) into the power system. Adjusting charging according to energy prices or participation in markets product can both benefit the
2. MARKET INTEGRATION

power system and represent an immediate economic incentive for fleet operator and EV owner. Furthermore, the study of current market conditions provides a good opportunity for shaping the recommendations and requirements for future markets to come. For the above reasons this thesis, and projects such as EDISON and the University of Delaware’s Vehicle-To-Grid (V2G) programme, uses existing markets for the investigations on EV utilization concepts. There are, however, shortcomings in the current markets that need to be addressed as part of DER market integration research: Firstly, requirements in terms of minimum bid sizes may represent a barrier for market entry. This issue was one of the main reasons the Virtual Power Plant (VPP) concept was originally proposed. The need for such an entity may decrease as the market evolves, but is, at least for now, a necessity for not only meeting capacity limits but also to manage the complexity of market involvement on behalf on individual EV owners. The use of VPP aggregation vs. distributed control is covered in more detail in chapter five “Control Architecture”. Secondly, since power markets were not built for DERs such as EVs, the flexibility and services of such units may not be appropriately rewarded if the mechanisms and products of the markets are left unchanged. A lot of attention is therefore given to designing the future markets that will better facilitate the integration of DERs. This is the main purpose of projects such as EcoGrid.EU (19). Finally, the distribution grid may be subject to new kinds of markets. This may help ensure a fair, safe and efficient utilization of the LV network. This is touched upon in chapter three “Grid integration” in this thesis.

2.2 Related Work Within Area

As part of the core publication, B, three projects was investigated in terms of their approach to market integration. See figure 2.1

![Figure 2.1: Market integration comparison - Comparison of the market integration approach of three EV projects](image)
As can be seen in the figure, University Of Delaware (UD) V2G is the only of the three projects that actively investigated the aspect of interfacing with the regulation market. The work by UD V2G within advanced EV utilization deserves special mention in this section due to their focus on this more advanced market approach and their practical demonstrations of active participation in such a market. Market participation was achieved by forming a VPP-like constellation and by partnering with a large battery-based regulation provider. The description of these demonstrations and the associated economics incentives is found in (20, 21). While UD V2G is unique in terms of the results they have achieved, numerous other researchers have investigated integration with either spot markets, ancillary service (A/S) markets or a combination of the two. In the paper (22), Rotering uses price forecasts and dynamic programming in a demonstration of both spot market based charging cost minimization and A/S provision. In a case based on markets in California, it is shown how daily charging cost can be reduced from $0,43 to $0,2. The daily profit of regulation service participation is estimated to be $1,71. In the article (23), Kristoffersen describes a fleet operator charging according to spot marked prices while considering typical driving patterns. The article suggests using either linear or quadratic programming to plan charging, depending on whether the fleet operator can influence market prices i.e. being a price taker vs having market power. In a report by Heesche (24), the author estimates the charging costs based on different charging strategies and mix between the spot and regulation market. Charging costs can, for some night charging scenarios, be cut in half when using smart charging instead of “dumb” charging. The estimated savings, however, is less than EUR 10 per month and are unlikely to be large enough to incentivize smart charging. Especially when considering that the market energy price is typically only a small fraction of what the EV owner pays per kWh. In Denmark only 15-25 percent of the energy bill is the energy price, the rest is taxes and fees.

Letting the tax component of the energy price increase and decrease as a function of the time of use, can strengthen the economic incentive of smart charging in the future.

2.3 Thesis Work and Contributions

Core publications part of the PhD study have described how the charging of a fleet of EVs can be based on hourly spot market prices or regulation signals. The following sec-
2. MARKET INTEGRATION

tion covers work done as part of the EDISON project, a comparison between American and European A/S products and, finally, a few demonstrations on A/S provision.

2.3.1 Market Integration in EDISON

As previously shown, EDISON choose to focus on existing markets and in this case on the Nordic Spot day-ahead energy market. The first step taken was an investigation of how a Fleet operator would be introduced in the setup of the spot market. The following figure 2.2 illustrates the approach used.

![Figure 2.2: Market integration in EDISON - The introduction of a fleet operator in the EDISON project](image)

The figure shows some of the existing market roles (Retailer, production- or load balance responsible) to which an actor, such as the fleet operator, would be associated.

In a real market scenario the fleet operator would bid on energy based on historic prices and the expected demand of its fleet. For the demonstrations done in EDISON however, the bidding process was neglected and it was shown how charging cost could be minimized if coordinated directly with known spot day-ahead energy prices. Rather than spot market integration it can be argued, this reflect a scenario where a dynamic energy tariff is used for charging.

Figure 2.3 shows a piece of demonstration software made in EDISON and illustrates how charging would be moved to the cheapest hours during night.
2.3 Thesis Work and Contributions

Figure 2.3: Smart charging - The charging schedule (bottom graph) places charging in hours where prices are low (middle graph).

For charging planning, linear optimization was used. More information is available in the core publication E and in chapter seven “Optimization”. Since energy prices are generally fixed for EV owners there are no immediate economic incentive for smart charging as done in the optimization. If energy is purchased through a retailer through the spot market it could, however, mean a lowering of charging prices. Using the spot prices directly in the cost estimation does not give an accurate impression of the real savings an end user would see. Rather this would depend on the bidding strategy of the fleet operator/retailer.

2.3.2 Comparative Study between Ancillary Service Markets

A type of markets that could offer higher savings, or even a profit, for the EV owners and fleet operators, are the A/S markets.

As mentioned previously in this chapter, UD V2G has already proven that there is a potential for connecting a fleet of EVs with the regulation market in the PJM area. To better understand both the requirements, potential barriers and type and shape of economic compensation that different markets represents, an investigation has been made. The goal was to compare the conditions under which UD V2G successfully demonstrated market integration with the conditions in the Danish A/S and regulation markets as part of European Network of Transmission System Operators for Electricity (ENTSO-E). The summery of this investigation can be seen in table 2.1.
2. MARKET INTEGRATION

<table>
<thead>
<tr>
<th>A/S Market</th>
<th>Area</th>
<th>Control method</th>
<th>Contracting</th>
<th>Minimum bid size (MW)</th>
<th>Responsiveness requirement (To full capacity)</th>
<th>Capacity compensation</th>
<th>Average capacity payment (MW-Hr)</th>
<th>Energy payment (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency regulation</td>
<td>PJM (USA)</td>
<td>Control signal</td>
<td>Day ahead, One-hour blocks</td>
<td>0.5</td>
<td>5 Min</td>
<td>Energy</td>
<td>-</td>
<td>12.5 EUR A.</td>
</tr>
<tr>
<td>Synchronized Reserve</td>
<td>PJM (USA)</td>
<td>Control signal</td>
<td>Day ahead, One-hour blocks</td>
<td>0.5</td>
<td>10 Min</td>
<td>Energy</td>
<td>-</td>
<td>7.3 EUR B.</td>
</tr>
<tr>
<td>Manual regulation reserves</td>
<td>DK west + DK east</td>
<td>Manual</td>
<td>Day ahead, One-hour blocks</td>
<td>10</td>
<td>15 Min</td>
<td>Capacity and energy</td>
<td>1.97 EUR C. up west 0.08 EUR C. down west 0.49 EUR C. up east 0.86 EUR C. down east</td>
<td>N/A</td>
</tr>
<tr>
<td>Primary Reserve</td>
<td>DK west</td>
<td>Frequency sensing</td>
<td>Day ahead, Six-hour blocks</td>
<td>0.3</td>
<td>30 Sec</td>
<td>Capacity</td>
<td>56.4 EUR D. up 16,85 EUR D. down</td>
<td></td>
</tr>
<tr>
<td>Secondary reserve</td>
<td>DK west</td>
<td>Control signal</td>
<td>Purchased on a monthly basis</td>
<td>N/A</td>
<td>15 Min</td>
<td>Capacity and energy</td>
<td>N/A</td>
<td>Based on spot- and intraday regulation market prices</td>
</tr>
<tr>
<td>Frequency controlled normal</td>
<td>DK east</td>
<td>Frequency sensing</td>
<td>Purchased on a monthly basis</td>
<td>0.3</td>
<td>2.5 Min</td>
<td>Capacity</td>
<td>78.36 EUR E. up 58.87 EUR E. down</td>
<td></td>
</tr>
<tr>
<td>operation reserve</td>
<td>DK east</td>
<td>Frequency sensing</td>
<td>Day ahead, Six-hour blocks</td>
<td>0.3</td>
<td>30 Sec</td>
<td>Capacity</td>
<td>31.06 EUR F. up</td>
<td></td>
</tr>
</tbody>
</table>

By comparing the A/S markets listed in the table, the following observations can be made. A/S contracting works in pretty much the same way across the ENTSO-E and PJM A/S markets. The Transmission System Operator (TSO) or Regional Transmission Organization (RTO)/(Role for PJM) will choose from a set of bids for up and down regulation reserves, the providers will be informed about accepted bids and the final compensation will be settled. The length of the time interval for which the A/S is contracted, and the time-of-contracting, however, varies from case to case. These differences should mean little to a fleet operator.

Most of the ENTSO-E markets described here are frequency controlled. An exception is the secondary reserve of DK west which is somewhat comparable with the regulation market of PJM in regard to activation mechanism i.e. a positive or negative power set-point sent from the TSO/RTO to the provider. If a provider using an EV fleet wish to participate in the frequency controlled A/S markets of DK west and DK east it will need to use frequency sensing equipment as part of the control system.

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Table 2.1: A/S Market comparison - Comparison between ENTSO-E and PJM markets

A. 2010, annual report, Regulation Market clearing price, including opportunity cost source: www.monitoringanalytics.com
B. 2010, annual report, Tier 2, Mid-Atlantic Subzone of the RFC Synchronized Reserve Market source: www.monitoringanalytics.com
C. 2010, average based on market data extract, source: www.energinet.dk
D. 2010, average based on market data extract, source: www.energinet.dk
E. 2010, average based on market data extract, source: www.energinet.dk
F. 2010, average based on market data extract, source: www.energinet.dk
2.3 Thesis Work and Contributions

This equipment will have to satisfy certain requirements on accuracy and measurement resolution.

Power and responsiveness requirements differ somewhat from market to market. For Frequency Controlled Disturbance Reserve (FDR) and primary reserve, the minimum bid size is 0.3 MW while the other markets investigated operate between 1 MW to 10 MW. This makes FDR and primary reserve suitable for participation by smaller EV fleets in the early stages of EV integration. The responsiveness requirements of the markets are all easily satisfied by an EV fleet. A demo V2G vehicle as described in (21) was able to respond on a sub-second timescale with its full capacity where as the fastest Danish A/S markets listed in this report requires full capacity within 30 Seconds.

The payment in the A/S markets generally increase as a function of how much power can be supplied in how short a time. Common for most ENTSO-E A/S markets described here is that they only reward capacity and not energy. The manual regulation reserve does not seem suitable for EV fleets since it offers a poor compensation for capacity and requires substantial amount of energy to be available for continuous supply. It is argued in (21) that it is currently less economically feasible to supply larger amounts of energy back to the grid due to roundtrip losses and a relatively low compensation pr. kWh in most markets.

The remaining four A/S markets in Denmark have much higher compensation. This is especially true for Primary Reserve and Frequency controlled Normal operation Reserve (FNR). FDR offers a lower average capacity compensation than FNR even though the former has higher requirements to responsiveness. This can be attributed to the fact that FDR is invoked less often. FDR can, in this aspect, be compared to synchronized reserves in PJM and could offer the same trade-off between compensation and EV battery lifetime preservation.

As previously mentioned, bid size requirements can be meet by the use of an aggregated group of vehicles. The concept of using multiply resources to meet a demand is mentioned in the “combined delivery” sections of the “Ancillary services to be delivered in Denmark - Tender conditions, valid from 1 January 2011” manual of Energinet.dk. Here it is stated that a delivery can be made up from several production or consumption units with different properties which collectively can provide the required response within the required response time.
2. MARKET INTEGRATION

For several of the markets, however, a delivery is not allowed from a combination of producing and consuming units. It will therefore be relevant to establish if an EV delivering power back to the grid (V2G) will be considered a “producer”. Will, for instance, a fleet operator be allowed to meet an up regulation request by making some EVs reduce load and having others deliver power back.

2.3.3 Providing Ancillary Services in Denmark

Having investigated A/S market participation by EVs, the Thesis Author participated in two demonstrations where two kinds of physical units were made to react on market signals.

Based on the market investigation, the secondary reserve market of DK was chosen since the regulation sum signal, provided by Danish TSO Energinet.DK, is both a meaningful and easily implementable input to the test. The secondary reserve signal is a MW value sent from the TSO to a group of providers and is positive or negative depending on the need of either up or down regulation. The sum signal is all the individual signals added together and is used since individual “TSO to provider” signals are kept confidential.

The first test was performed towards a battery setup as described in the core publication D. The test demonstrated how a set of lithium batteries through a controllable charger and inverter, could be made to charge or discharge according to the real-time balancing need of the TSO. The result can be seen in figure 2.4.

The upper graph in the figure shows the charging schedule sent to the battery setup compared to the target value (sum signal) sent by the TSO. For this test Marra D constructed and prepared the physical setup (nicknamed the “Table-To-Grid” setup). The lower graph in the figure shows measurements from the battery management system (BMS) attached to the batteries.

The Thesis Author decided to repeat the experiment, using the full system architecture and communication solutions described later in this thesis, towards a real EV (the Toyota Scion eBox). The exact same signal was sent to the EV as was used towards the battery-setup. The result can be seen in figure 2.5.

It can be seen from the figure that the EV precisely follows the aggregated regulation signal. The regulation signal in question represents a period with many fluctuations with a close to equal amount of up and down regulation periods. This has a positive
2.3 Thesis Work and Contributions

Figure 2.4: Table-To-Grid setup - Using a set of lithium batteries to respond to a LFC sum signal sent by a TSO. 
source: Marra, core publication D

Figure 2.5: EV setup - Using an EV to respond to a LFC sum signal sent by a TSO
2. MARKET INTEGRATION

impact on the State-Of-Charge (SOC) which stays close to 50 percent throughout the whole period. A stable energy level makes planning easier when having to meet a certain energy target plus reduces wear on the battery due to deep cycles. For periods with less variation, e.g., longer periods dominated by either up or down regulation, an aggregator will have to depend on having sufficient vehicles in its portfolio as to even out the influence on individual EV SOC levels.

The experiments prove that A/S via EVs is technically possible - proving the business case and understanding the impact on batteries still is in need of research.

2.4 Sub-conclusion

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.

2.4.1 Contributions and Results by the Thesis

The first findings and contributions, as part of the EDISON project, were that:

- EVs can be connected to the NordPool spot day-ahead energy market through a VPP-based fleet operator if adhering to the appropriate market roles and responsibilities.

- Backend software have been developed and have been used to charge EVs (real and simulated) according to energy prices extracted from the energy market.

The next step taken was looking at A/S markets to understand how the market used in UD V2G compares with the ones available in Denmark, the results were that:

- Although variations exists between the markets, most constraints and requirements can be overcome by the use of a fleet operator and the aggregation of EVs.

- The FNR market of DK east is found to offer the highest average capacity compensation but would require frequency sensing to be implemented.

- A/S based on power capacity rather than energy, is a good match for the capabilities of an fast-response, high-power DER such as an EV.
• The secondary reserve market of DK west is a close match to frequency regulation in the PJM area and is a good starting point for a field test.

• The EnergiNet.dk rules on “combined delivery” will have to accommodate V2G enabled EVs.

Based on the findings from the market analysis the following was demonstrated:

• One of the Danish markets were chosen and it was demonstrated that two units - a Table-To-Grid setup and an eBox EV - can follow the sum signal sent out by the TSO as would be the case when participating in said market.

• The experiments carried out by the Thesis Author have proven that an EV can be made to react within a few seconds (full communication stack latency + charger/inverter ramp-time) which would easily satisfy all markets considered.

2.4.2 Discussion and Recommendations

Market integration concepts for EVs will vary based on local market conditions and are, for the centralized architectures, tightly linked to the business cases chosen by the fleet operator. Smart charging, as covered by EDISON and e-mobility, can be seen as a first approach to market integration by allowing the EV to respond to variable energy prices on the energy market. The V2G equipment tested by UD V2G can be seen as the second step where the EV increases its potential as a resource to the grid and more market integration concepts becomes possible. New market integration concepts might occur over the coming years to better facilitate DERs as part of the smart grid concept.

It is recommended to further examine the FNR and Primary reserve markets since they, at the time of the investigation, are found to offer the best economical compensation. This would require new functionalities to be implemented in the technical platform used by the fleet operator in order to facilitate frequency sensing as required in these markets.

It is important to note that the economic attractiveness of a specific market can change over time. If, for instance, several EVs enter a specific market they might, in time, saturate the need of certain services. Also, nightly energy prices may increase as more EVs delay their charging to the same hours. As long, however, as most European
2. MARKET INTEGRATION

countries keep their ambitious energy targets, it is likely that the flexibility of EVs will be both needed and duly rewarded on the markets.

This chapter have described the use of the energy market for a charging cost reduction and the A/S market for a potential profit. An advanced scheme could be to combine both of the above objectives, i.e., planning EV charging based on both energy prices and balancing needs. This is left for future research.
Grid Integration

This chapter deals with the distribution grid as part of the “Domain interfaces” investigations of this thesis. The following publications constitute the core contributions done by the Thesis Author to this area:

A Coordination Strategies for Distribution Grid Congestion Management in a Multi-Actor, Multi-Objective Setting.

E Prediction and optimization methods for electric vehicle charging schedules in the EDISON project.

The publications will be referred to by their letter (A,E) in the following.

3.1 Introduction

The local distribution grid, to which the Electric Vehicle (EV) will connect, has a large part to play within intelligent EV integration and may be one of the most complex issues that EV integration research will have to address. The core challenge is that the EV represent a larger load than what is normally attached to residential feeder lines and can therefore violate the Distribution System Operators (DSO) operational constraints such as:

- **Voltage limits.** Keeping the voltage at any point in the grid within a certain range (power quality obligation towards customer).
3. GRID INTEGRATION

- **Thermal limits of cables and transformers.** The energy transferred through equipment and conductors compared to the current rating of such components (equipment lifetime consideration).

- **MVar limits.** Bands for reactive power exchange at the connection between the distribution grid and the transmission level (obligation towards transmission system operator).

In this chapter the focus is on congestion issues, i.e., a situation in which the demand for active power transfer exceeds the transfer capability of the grid.

Where charging according to market prices may be the first obvious approach when talking about system-wide concepts (See chapter two “Market integration”), moving the EV load away from the household peak load is an obvious first approach when turning the attention to the distribution grid and congestion issues. It has, however, been established that the combined load of EVs in themselves can cause problems for the grid even if charging when base-load is typically low. Add to this that many of the system-wide concepts considered will tend to cluster charging in time e.g. all reacting to the same low charging cost or reacting to a regulation need at a higher level of the power system. This behavior is by the IBM partners in the EDISON project termed "The EV lemming effect". (25)

Making the EV charging “compatible” with the local grid can either be implemented as a hard requirement imposed on fleet operators, or as a new type of LV grid ancillary service which a fleet operator will be compensated for supplying (but still may be forced to provide).

When researching EV grid integration, the three following steps can be followed:

1. Conducting grid impact studies to assess the problem.

2. Suggesting strategies to mitigate grid issues.

3. Validating strategies using simulations and in-field tests.

The Thesis Author have sought to understand issues relating to the first of the above points, grid impact studies, by going through a number of publications investigating this topic. The emphasis of this thesis has been on the second point, suggesting strategies to mitigate grid issues (in the form of congestion), and this primarily from the point
3.2 Related Work within Area

The EDISON project has made contributions to the area of grid impact studies which is documented as part of the projects technical reports (26). Here, a part of the Bornholm grid has been simulated and the result of different EV penetration levels was investigated in terms of cable and transformer loading as well as voltage drops for part of the 400 V, 10 kV and 60 kV grid. The conclusion was that the 400 V grid was most sensitive with voltage drops as the biggest problem. All grids could accommodate up to 20 percent EV integration if the charging was limited to 1 phase/16 Amp/230 V charging (3.6 kW). The charging strategy (“dumb” charging vs. smart charging) was shown to have a major impact on the EV integration level supported. An important comment relating to the fleet operator made by the report is "The fleet operator has the ability to limit its consumption, however, with the current market setup, there are no incentives to do so."

Another project, MERGE, have performed comprehensive investigations on the topic (27) and concludes that for LV networks "large scale EV integration affects quality of service and may cause significant technical problems". MERGE bases the study on several EV penetration scenarios, grid topologies and charging methods. MERGE simulations indicate that congestion problems increase when considering "Dumb" charging and rural grid topologies.

The effect grid topology has on simulation results is also visible when comparing publications done by Shao (28) and Marre (29) respectively.

Shao demonstrates that a strong urban distribution grid supports a 100 percent EV integration considering both voltage limits, harmonics and thermal loading of cables and transformer. In contrast Marra demonstrates that the transformer of a rural/residential topology can be overloaded at relatively low EV integration levels.
3. GRID INTEGRATION

It can be concluded from the above that grid impact is a real issue and should be handled accordingly. This is especially true when considering the provision of system-wide market services done by V2G UD (20) (using an EV fleet for regulation services). Here EV charging will both be clustered in time and to be done at high power levels, i.e., 120 V, single phase with up to 80 Amps (9.6 kW) thus adding to a potential grid issue.

The next step for academia is to suggest congestion mitigation strategies. Also in this area some good contributions are available.

In (30) Shao describes a demand response strategy for load shaping considering the constraints of the local transformer. The strategy also includes considerations to user preferences, the priority between the individual loads in a household and the privacy of data. It is shown how household base load plus controllable load (AC, Water heater, EV) will exceed transformer ratings in certain hours. A home area network control flowchart illustrates how the controllable loads are scheduled depending on their priority and convenience preference. By employing the strategy it is shown how the combined load of the households is kept within the transformers capacity rating.

As part of the EDISON project, dynamic grid tariffs were investigated. In this scheme, a price is sent that can reflect system-wide energy prices while including a cost-component representing the state of the grid to which the individual recipient is connected. This means that even if energy prices are low, a local price may be high due to local congestion. The use of dynamic grid tariffs have been described by Connell in (31).

Another notable contribution to congestion mitigation strategies combined with smart charging has been done by Binding and Sundstroem in (32). The authors uses discrete and continuous state variables to simulate a fleet of electric vehicles and the distribution grid. The paper introduces a Charging Service Provider (CSP) which goal it is to meet EV owner energy demand, minimize charging energy cost and at the same time avoid grid bottlenecks. The solution may depend on a number of iterations between a DSO and the CSP before the fleet charging plan of the CSP is “pre-approved”. The DSO uses a load flow or flow Network method to validate the impact of a certain fleet charging plan sent to it by a CSP. The solution represent an advanced approach to handling congestion issues.
3.3 Thesis Work and Contributions

The latter two of the above publications seek to combine grid congestion mitigation with the minimization of charging costs. This type of combined objectives is an advanced and very relevant area of EV integration research and is also the area to which this thesis wish to contribute.

3.3 Thesis Work and Contributions

The focus of this section is on how grid constraints may influence the operation of the fleet operator.

Ideally a grid congestion mitigation strategy should be implemented that respects and supports the operational goals of all stakeholder involved in EV integration. The key stakeholders identified in core publication A is the DSO, the fleet operator and EV owner. The approach used is to list the key operational tasks that each stakeholder would need to undertake based on their value drivers. These tasks are then divided into stages based on in what phase they are performed. See figure 3.1.

<table>
<thead>
<tr>
<th>Stage</th>
<th>I. Planning</th>
<th>II. Scheduling</th>
<th>III. Operation</th>
<th>IV. Settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV Owner</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>FO</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSO</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.1: Map of base-case operations - Mapping of stakeholder key operations to stages.

The stages used are inspired by functional levels found within industrial automation. “Planning” is the stage in which commitments and contracts are made. In the “Scheduling” stage, available resources are known and they are coordinated and prepared for the operation stage. The stage “Operation” is about pure execution of
3. GRID INTEGRATION

schedules and the handling of real-time events. Finally the “Settlement” stage is about the financial aftermath.

The purpose of the map is to illustrate the task of each participant before a congestion mitigation strategy is introduced. One special operation ”Charging interruption” found in the “Operation” stage is suggested since it could represent a vital last resort function for the DSO to stop the charging of an EV if all other grid congestion mitigation strategies fail. The suitability of a strategy could then, among other things, be measured on the amount of times it would be necessary to invoke such a function.

Core publication A then describe the concept behind three individual strategies which are:

- Distribution grid capacity market
- Advance capacity allocation
- Dynamic grid tariff

For each approach, a new map is drawn where operations required specifically for the strategy in question are presented. The dynamic grid tariff strategy is similar to what is proposed by Connell [31], i.e., generate a time and grid-location dependent price for grid usage based on expected nodal consumption levels.

The distributed grid capacity market strategy introduces a ”market operator” which defines prices based on demand and supply. Aggregated schedules for demand and prices are sent back and forth between market operator and fleet operators in an iterative process.

The final strategy, advance capacity allocation, the one described and proposed by the Thesis Author, is illustrated in figure 3.2.

The idea behind this approach is that the DSO would calculate available capacity for each feeder-line based on transformer and cable ratings and the expected conventional load curves. The households attached to a certain feeder-line would then be given a certain share of available capacity (kW), which could be allocated to the fleet operator representing them. To avoid inefficient utilization of available grid capacity due to unused capacity shares, a second step is added to the strategy where fleet operators can trade their allocated capacity in an over-the-counter manner.
3.4 Sub-conclusion

Possible advantages and drawbacks of each strategy is discussed in A in terms of complexity, value and risk.

A benefit for the advance capacity allocation strategy is that it would be relatively easy to implement. The strategy, however, relies on efficient and reliable trading between fleet operators in order for the capacity to be used efficiently. The strategy does not deal with real-time operational requirements such as harmonics and voltage limits which needs to be handled separately.

A very early attempt to incorporate grid constraints in EV charging is found in core publication E where the charging power can be limited based on a time based constraint. This time-based constraint could be based on the capacity allocation strategy.

3.4 Sub-conclusion

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.

3.4.1 Contributions and Results by the Thesis

A number of grid impact studies have indicated that congestion issues may occur at EV penetration levels as low as 20-40 percent depending on charging strategy, charging power and the topology and level (e.g. 400 V vs 10 kW) of the grid in question.
3. GRID INTEGRATION

The Thesis Author have contributed to the area with an investigation on grid congestion mitigation strategies in which it is concluded that:

- Operation maps can help understand the impact of coordination strategies on the operations and interactions of stakeholders.

- Grid considerations may have to co-exist with other objectives in the charging management of EVs (such as system-wide services).

- Coordination and information exchange in earlier stages can reduce complexity and benefit both the fleet operator and DSO.

- There may be a trade-off between ease of strategy implementation and optimality. A compromise may be necessary for the first real-life implementations.

- A suitable strategy for coordination between DSOs and fleet operators will improve each stakeholder’s ability to reach its objectives considerably.

If a strategy such as advance capacity allocation is used, the available per-feeder capacity may be known by the fleet operator when planning EV charging in correspondence with market contracting. These capacity limits can be included as constraints in an optimization method.

3.4.2 Discussion and Recommendations

Full penetration of EVs will undoubtedly mean extending and enforcing the grid in some locations. If EV charging is coordinated appropriately, however, such extensions may not need to accommodate a worst-case scenario where all EVs are charging at the same time.

An important question is what objective will have the greatest monetary value: using EVs for system-wide services or to charge according to local grid conditions.

Short term, with the existing distribution grids, the DSOs operational limits will trump any objective that a fleet operator may have in the power market. For the planning of future distribution grids, however, the many possible system-wide uses of the EV must be thoroughly considered.

Should distribution grids be subject to heavy extensions so that they can facilitate a lot of EVs charging simultaneously in response to e.g. transmission level wind
availability!? or should expansions, and the associated cost, be kept at a minimum by requiring all EVs to charge according to available grid capacity.

It is reasonable to assume that the DSO will require an real-time emergency intervention mechanism that curtails EV charging if some of the operational limits are violated. It would represent a big challenge to EV introduction in general if such events are allowed to occur frequently.
3. GRID INTEGRATION
4

EV Owner

This chapter deals with the Electric Vehicle (EV) owner as part of the “Domain interfaces” investigations of this thesis. The following publications constitute the core contributions done by the Thesis Author to this area:

A Coordination strategies for distribution grid congestion management in a Multi-Actor, Multi-Objective Setting.

E Prediction and optimization methods for electric vehicle charging schedules in the EDISON project.

The publications will be referred to by their letter (A,E) in the following.

This chapter also present some material not yet published in the ”Early investigation of real driving data” section. While the work in this area is not yet complete, it is included here to supply some early examples on how real EV usage data may be used by a fleet operator in its operation. The data can be used as input to the prediction and optimization method employed by a fleet operator.

4.1 Introduction

The EV owner is easily the most important stakeholder in EV integration. Intelligent EV integration depends both on the EV owner accepting her or his role as an active prosumer and that the behavioral patterns of said owner support flexibility in charging.
4. EV OWNER

Regarding the first point, owner acceptance, it is important to understand the motivations of EV owners. Early research [33] point to three main parameters that influence people’s willingness to invest in an EV:

1. The EV’s ability to meet transportation needs - especially in regards to range.
2. The total cost of ownership compared to a traditional car.
3. The availability of sufficient EV charging infrastructure.

The intelligent EV utilization concepts investigated as part of this thesis, can potentially influence the second of the above factors - total cost.

For any software developed to achieve controlled charging, it is reasonable to assume that owners would like to have interfaces (mobile apps, web pages etc.) through which they can stay informed and empowered. Also, the owner is more than likely to favor convenience and ease of use.

Such convenience can be achieved through:

1. Transparent frame conditions for the use of controlled charging captured in a well-formed Service Level Agreement between owner and fleet operator. (Example: always charge immediately to 50 percent energy for emergency trips)
2. That the fleet operator can precisely predict the needs and flexibility of the EV owner and approach the owner with accurate and relevant suggestions for controlled charging. (Example: The fleet operator can suggest that charging can be delayed until morning hours if the owner never leaves home before noon)

The second of the above points, assessing the precise flexibility of the EV owner, is also important in order to maximize the EVs value as a resource. The flexibility relates to EV owner plug in patterns which are defined as the periods in time in which the EV is connected to the power system and thus capable of uni or bi-directional energy transfer. While the EV owner may plug in the vehicle at many different locations and for different need scenarios, only one type of plug in period is of interest for smart grid integration:

- A period that is long enough, compared to the energy need, so that they grant flexibility for delaying charging in time.
4.2 Related Work within Area

- A period that is **predictable in nature** and recurs according to a certain pattern.

In general, two categories of commuter charging suit the two above criteria: workplace charging and night charging. In contrast, most fully-public charging options (such as DC fast charging) are used for range extension, i.e., used sporadically to gain extra kilometers of range. The latter category therefore does not meet either criterion.

A general expression of the flexibility can be formulated as:

\[
Flexibility = f(duration, energyNeed, predictability)
\]  

(4.1)

The work presented in the thesis investigates plug in periods in terms of the above parameters and it is shown how such periods can be predicted and what role they may play for intelligent EV utilization concepts and the fleet operator.

4.2 Related Work within Area

Most driving pattern studies conducted have relied on data from traditional internal combustion engine (ICE) cars for their investigations. This is due to the fact that any large quantity of driving data collected from EVs are, as of yet, difficult to come by. ICE vehicle data is a reasonable starting point if EVs are expected to fulfil the same role as the ICE vehicles investigated, e.g., urban commuting.

Using ICE vehicle data can, for instance, be useful in studies investigating an EVs ability to meet driving needs. Comparing a typical EVs range of 100-180 km with the average Danish driving distance by commuters of 29.48 km (Danish National Transport Survey) it seems that most daily driving patterns can be satisfied. It is, however, also necessary to consider the variance e.g. how often people drive much longer than the 29.48 km.

In (34) Pearre conducts a statistical study based on 484 ICE vehicles to assess a vehicle owners range needs compared to what would be supported by an EV. Pierre approaches the problem by investigating how many times, over one year, the range of an EV would not suffice. It is shown that nine percent of the sampled vehicles never exceed a daily driving need of 160 km, meaning that this group would be viable candidates for adopting EVs. Pierre then shows that allowing six “range violations” per year would increase this number to 32 percent. This means that if roughly one third
of the sample group would find an alternative solution, e.g., rent an ICE vehicle, for the up to six days with the longest driving distance, an EV could satisfy the remaining driving need for this entire group.

Having investigated an EVs ability to meet the primary function, driving, the attention can be turned towards the EVs potential for intelligent EV utilization concepts.

A study by Wu (35) address daily driving patterns as done by Pierre, but also investigates EV availability for controlled charging. Here "availability" is interpreted as all the time periods in which the vehicle is not driving. The sample presented by Wu shows a very high degree of availability - especially at night and during noon. This availability, if representing times in which an EV is both parked and plugged in, is an early first measure of the degree to which it can participate in concepts such as smart charging.

The investigation of such "availability periods" is taken further in (36). Here, the authors uses a semi-Markov model to predict the next place of arrival and stay duration of a vehicle. The arrival locations are shown to be predictable with 84 percent accuracy using the proposed method. As with the above studies, ICE vehicle data is used and are based on GPS measurements.

The authors clusters geographically close GPS measurements for when the vehicle is parked to create a number of locations. The importance of each location, in terms of usefulness for controlled charging, is then estimated using a point system. Points are given depending on the number of stopovers at the location, the average stopover duration and the spread of this duration. The method is very useful when going beyond night charging for EVs and identifying other periods that are sufficiently long and predictable. For private commuting vehicles this would, however, most likely be limited to the home and workplace location. Hidden Markov models have previously been applied to trip prediction by Simmons in (37) which also addresses the specific purpose of a trip.

There are, however, investigations for which you need "real" EV data. For instance when it comes to understanding how often the EV owner will perform the action of plugging in the vehicle. Some of the largest organised EV trails yielding such data, are the German Mini E Berlin project and the Danish Test-An-EV programme. An investigation of EV owner acceptance and behavior based on Mini E Berlin is described by Cocrona in (38).
The research on owner patterns based on real EV trails and the impact on EV fleet charging optimization is still in need of investigation and is therefore pursued by the Thesis Author.

4.3 Thesis Work and Contributions

As stated above, this thesis focuses on the use patterns of the EV owner as they relate to smart charging. It is especially important that the fleet operator understands and adheres to driving demands. See core publication A for a short description of expected EV owner requirements and value drivers.

4.3.1 Simple Prediction based on Driving Data

The first study was based on ICE vehicle patterns as part of the AKTA driving set (Centre for Traffic and Transport (CTT)). The AKTA data was based on a total of 360 vehicles, which were followed from 14 to 100 days between 2001 and 2003 and is biased towards driving seen in the greater Copenhagen area.

It was, in core publication E, suggested to use a simple exponential smoothing model for predicting the duration of night stopovers (see figure 4.1).

![Figure 4.1: Expected night availability as function of variance](image)

*Figure 4.1: Expected night availability as function of variance* - Illustration of how the period used by a fleet operator for controlled charging may depend on the average value and standard deviation of plug ins and outs.

In the driving data, stopover periods were periods in time where the car would be parked. The authors filtered the data to only include nightly stopover periods and some outliers were removed. These periods could then be considered suitable candidates for smart charging and where used as input to a binary optimization (described in chapter seven: "Optimization"). The following exponential smoothing function was used:
4. EV OWNER

\[ X_{n+1} = (1 - \delta)X_n + \delta S_n \] (4.2)

In the above, \( X_1 = S_1 \) and \( S \in \mathbb{R}^n \) is historic stopover data for a given vehicle. \( \delta \in [0; 1] \) is a fixed parameter determining the weight that new observations are given compared to historic data. A low \( \delta \)-value will result in new observations having a higher impact on the prediction.

The paper went further by investigating the relationship between the variance and mean of start and stop times and the value of the objective function and to test the robustness of the solution. A suggestion of the authors was to let the time interval used for smart charging depend on the variance (standard deviation) in stop and start times. A drawback of the above method is that cyclic daily or weekly variations are not taken into account.

The method was included by the Thesis Author in the demonstration software developed in EDISON. The following figure 4.2 shows a part of a fleet operator interface where the lines in the top portion “EV charging availability” illustrate how the fleet operator transitions from using a static guess/profile of night availability to using a prediction based on exponential smoothing. The upper line is the “measured availability” while the dashed line underneath is the “predicted availability”.

![Figure 4.2: Implementation of predictions - Illustration of EV charging availability prediction by a fleet operator as implemented in EDISON software.](image)

The above represents a first approach to making predictions on night plug in availability and its active use by fleet operator aggregation software.
4.3 Thesis Work and Contributions

4.3.2 Early Investigation of Real Driving Data

The Thesis Author has investigated real EV driving patterns as part of the Danish Test-An-EV programme. The programme, orchestrated by the electric mobility operator (EMO), Clever, includes over 1600 Danish households over a three year period with a fleet of 184 EVs. The project is supported by the Danish Energy Agency and the Danish Transport Authority. The data has been stripped of personal information to protect the identity of the participants.

In the study, groups of eight to ten EVs are distributed to cities in Denmark, here the groups participate in a number of "rounds", each with a duration of approximately 3 months. In every round, each EV is given to a household. The households all receive, and hand back, the EVs at the same time. For this study, six cities have been chosen, each with two rounds as illustrated by figure 4.3.

![Figure 4.3: Full sample of vehicles - Approximately 50 EVs and 100 families driving in six different cities throughout the winter, spring and summer months of 2012.](image)

The above is the data used for the plug in investigation.

Figure 4.4 visualises the charging periods for a single vehicle from the Test-An-EV dataset during spring 2012. Notice that charging periods lies in the very beginning of each plug in period signifying that, what is commonly known as "instant" or "dumb"-charging, is used.
It has already been argued that the most important parameters for a plug in, in regards to controlled charging, are the duration, predictability and the energy demand for the next trip. These parameters are now investigated based on the recorded plug ins.

First, however, the sample is filtered to only include ”workday night charge plug ins”, i.e. a plug in starting after noon and terminating the following day before noon on a workday (monday to friday). Some of the vehicles have been excluded due to inactivity and/or lack of data.

Since a plug out event is not recorded in the data, it is assumed that the EV will remain plugged in until the next drive if it was plugged in at the end of the previous drive.

The averages for the full sample (illustrated in figure 4.3) is listed in table 4.1.

It can be seen from the numbers that the charge period is only roughly one third of the plug in period meaning that there, based on the average, is a lot of flexibility available in when to charge the battery. This is even though the batteries are charged to 100 percent and it typically takes considerably longer charging the last 5-10 percent


4.3 Thesis Work and Contributions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug in period duration</td>
<td>12:43:03</td>
<td>41 (Min)</td>
</tr>
<tr>
<td>Charge period duration</td>
<td>04:00:12</td>
<td>17 (Min)</td>
</tr>
<tr>
<td>Plug in period start SOC</td>
<td>49</td>
<td>4 (Percent)</td>
</tr>
<tr>
<td>Plug in period end SOC</td>
<td>100</td>
<td>2 (Percent)</td>
</tr>
<tr>
<td>Plug in period start</td>
<td>19:10:28</td>
<td>39 (Min)</td>
</tr>
<tr>
<td>Plug in period end</td>
<td>07:53:32</td>
<td>29 (Min)</td>
</tr>
</tbody>
</table>

Table 4.1: Plug in period averages - full set.

due to the BMS and its management of battery lifetime.

It can also be seen that the average State-Of-Charge (SOC) is relatively high at plug in, and that the plug out (Could be when EV owner leaves for work) is subject to less variance than the plug in (Could be when EV owner returns to his/her house). Such "fleet" information is valuable to an fleet operator for accessing the potential for controlled charging.

Subsets of the above data have been put to use in a few investigations described in the following sections. In these investigations, the sample sizes have been kept relatively small, this is due to the fact that the 2012 data, especially from late 2012, still needs to be thoroughly tested for completeness and correctness before it can be included in a larger study.

4.3.3 Plug in Patterns: Seasonal Changes

This study is an investigation of possible changes in plug in behavior due to seasonal changes. To this aim two samples are compared from the month of February and June 2012 - see figure 4.5.

![Figure 4.5: Winter vs. summer month](image)

Figure 4.5: Winter vs. summer month - Comparison between the plug in period parameters of the month of February and June 2012.

A study have been conducted to compare the plug in periods of ten EVs driving in February (February-set) with ten EVs used in June (June-set). Both the February-set
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>February -</th>
<th>June -</th>
<th>February -</th>
<th>June -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>12:32:30</td>
<td>11:38:20</td>
<td>04:12:35</td>
<td>04:12:35</td>
</tr>
<tr>
<td>SD</td>
<td>66 (Min)</td>
<td>31 (Min)</td>
<td>20 (Min)</td>
<td>20 (Min)</td>
</tr>
<tr>
<td>Plug in period duration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>04:06:02</td>
<td>04:12:35</td>
<td>04:12:35</td>
<td>04:12:35</td>
</tr>
<tr>
<td>SD</td>
<td>31 (Min)</td>
<td>20 (Min)</td>
<td>20 (Min)</td>
<td>20 (Min)</td>
</tr>
<tr>
<td>Plug in period start SOC</td>
<td>50</td>
<td>46</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>Plug in period end SOC</td>
<td>100</td>
<td>99</td>
<td>7 (Percent)</td>
<td>7 (Percent)</td>
</tr>
<tr>
<td>Plug in period start</td>
<td>19:40:15</td>
<td>20:06:29</td>
<td>56 (Min)</td>
<td>56 (Min)</td>
</tr>
<tr>
<td>Plug in period end</td>
<td>08:12:45</td>
<td>07:44:49</td>
<td>72 (Min)</td>
<td>72 (Min)</td>
</tr>
</tbody>
</table>

Table 4.2: Plug in period seasonal averages - February and June set.

and June-set of EVs are equally distributed between the same two cities. The results can be seen in table 4.2.

From an fleet operator point of view the February-set vehicles seems to have greater flexibility in that they are plugged in for longer durations. A possible reason could be an altered behavior due to changes in hours of daylight (People might get up later and arrive home earlier during winter).

It is however dangerous to claim such causality based on the limited amount of samples used in the data. Even if having the same distribution of vehicles betweens cities in each set may remove some geographical bias, it is still different families driving the vehicles and such bias can only be compensated for by increasing the sample size. The above should therefore be supplemented by other larger investigations.

4.3.4 Plug in Patterns: Familiarization

Another interesting study question is whether there is a change in plug in behavior when comparing the initial part of the test period with the last.

If, for instance, an EV owner plugs in less often due to increased “range confidence”, it will result both in less availability and, when the EV is available, a higher energy demand. The result is a significant reduction in flexibility as expressed in the flexibility function described in the introduction 4.1.

This study is illustrated in figure 4.6 and includes 12 EV test families distributed equally between four cities. The first, approximately 90 days, of a test period constitutes the initial period while the last 90 days represents the mature period. The result is presented in table 4.3.
4.3 Thesis Work and Contributions

Figure 4.6: Initial vs. mature use - Comparison between the first half and last half of the test periods during the winter/early spring months of 2012.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial - Mean</th>
<th>Initial - SD</th>
<th>Mature - Mean</th>
<th>Mature - SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug in period duration</td>
<td>13:03:43</td>
<td>52 (Min)</td>
<td>12:41:44</td>
<td>52 (Min)</td>
</tr>
<tr>
<td>Charge period duration</td>
<td>04:06:08</td>
<td>23 (Min)</td>
<td>04:03:55</td>
<td>15 (Min)</td>
</tr>
<tr>
<td>Plug in period start SOC</td>
<td>48</td>
<td>4 (Percent)</td>
<td>40</td>
<td>4 (Percent)</td>
</tr>
<tr>
<td>Plug in period end SOC</td>
<td>99</td>
<td>4 (Percent)</td>
<td>100</td>
<td>0 (Percent)</td>
</tr>
<tr>
<td>Plug in period start</td>
<td>19:04:47</td>
<td>47 (Min)</td>
<td>19:21:25</td>
<td>45 (Min)</td>
</tr>
<tr>
<td>Plug in period end</td>
<td>08:08:30</td>
<td>37 (Min)</td>
<td>08:03:09</td>
<td>27 (Min)</td>
</tr>
</tbody>
</table>

Table 4.3: Plug in period familiarization averages - Initial and mature set.
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Based on this sample there seems to be little difference between the initial and mature part of the test periods. Also the amount of plug ins are relatively stable throughout the two sets. The EVs seems, however, to be connected a bit longer (13:03 vs 12:41) in the initial period and for these 12 vehicles and test families, this results in the fleet having greater flexibility [4.1] and perhaps, value, for the fleet operator.

The relatively small sample size and time period in consideration makes the result more sensitive to vacation periods. Again, it is the aim to repeat the study when more data have become available.

4.3.5 Plug in Variance Case and Relation to Smart Charging

This section will concentrate on a single vehicle to illustrate how charging flexibility may be used for different purposes. An EV driving in northern Jutland have been selected. The EV has a total of 55 night workday plug ins over the three month trial period signifying a very frequent and consistent use. Figure 4.7 shows the SOC distribution at the start of plug in.

![Figure 4.7: SOC distribution for case EV - Distribution of 55 SOC measurements with a mean of 39 (SD 19).](image)

The vehicle is used for long daily commutes which is reflected in the relatively low average plug in SOC.

For the same vehicle, the cumulative distribution of plug in and plug out times are illustrated. For the sake of the illustration the distribution of the plug in times are "inverted" so that the "valley" in the graph represents a high probability of the EV being available to the grid. The variance of the SOC and Plug in/out distributions matters since a high standard deviation may can result in a higher risk for controlled charging. I.e. the fleet operator can underestimate the energy need or the amount of time available. It may be necessary to consider a trade-off between risk and benefit.
For this case it is riskier to postpone charging to the early morning hours between 5:30 and 6:45. The "risk-area" would increase if the distribution were more negatively skewed i.e. left tailed. If a specific "expected time of plug out" is chosen (i.e. 6:20) the fleet operator can tell the owner that this, based on the plug out distribution, would be appropriate roughly 90 percent of the time. The EV owner should than accept the slight risk of leaving with less energy than planned when plug out happens earlier than expected.

The only reason the fleet operator and owner would take such a risk is if the benefit of charging is high in the same hours where there is a small chance a plug out may occur. Decision making under uncertainty is left to chapter seven: "Optimization" later in this thesis.

This section concludes by showing some of the possible drivers for controlled charging. Data for all sources are collected for the same period (April to June) and part of Denmark (Western Denmark) as was the case for the family testing the EV.

Of the sources both wind and market prices seems to favour night charging. For wind, the average production is a bit lower during night but remains more stable than the demand which falls considerably. It is important to add that looking at the dynamic behavior in a sub-hour time-scale, wind production can exceed demand at several points in time. The graph only hints to the possibility of charging based on wind energy - not on power services such as regulation/ancillary services.

For a house-mounted PV however, there is little synergy to be found. The short period during the morning (around 6:20) where energy potentially could be drawn from PV to EV represents a high risk (for the EV leaving) small benefit (only few Watts of power) scenario.

In chapter seven "Optimization", the price of energy is used as motivation for controlled charging.

4.4 Sub-conclusion

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.
Figure 4.8: Plug in/out cumulative distributions and input for value functions - Visualisation of availability compared to the sources that may motivate controlled night charging.
4.4 Sub-conclusion

4.4.1 Contributions and Results by the Thesis

In a study based on ICE vehicles the following have been done:

- An approach to simple plug in period prediction based on exponential smoothing have been proposed.

- The above method have been implemented in demonstration software for EV fleet management as part of the EDISON project.

Next, it is demonstrated how real EV data may be used to investigate plug in behavior. This includes:

- A description of the main parameters that determines plug in periods usefulness for controlled charging.

- Early indications on the effects that EV familiarisation and different seasons may have on plug in behavior.

- A specific EV is used to illustrate plug in availability compared to different value-sources for controlled charging.

The author hopes that such investigations can help uncover the role and impact that EV owner plug in behavior has in regards to intelligent EV utilization concepts.

4.4.2 Discussion and Recommendations

The control systems managing charging, should know the plug in patterns of the EV owner as well as possible. This can both increase convenience by reducing the need of EV owner intervention in smart charging management, and at the same time make sure that the flexibility of the vehicle is used optimally without violating the driving needs of the EV owner.

Investigations on the Test-An-EV data indicates that there is a lot of charging flexibility available for the families included in the test programme (plug in period duration compared to energy demand). For a specific sample investigated, there seemed to be more flexibility available during a winter month compared to a summer month. EV driving familiarization does not seem to have a great impact on flexibility based on
4. EV OWNER

the small sample investigated. The studies should, however, be validated using a larger sample to reduce the sampling error.

The fleet operator will have to describe the risk/benefit trade-off of controlled charging to the EV owner, i.e., the EV owner must accept that the fleet operator may miscalculate the charging flexibility 1 out of $X$ times. Based on the plug out probability distribution the fleet operator may, for instance, choose an expected plug out time that in three percent of the cases will be later than the actual plug out. If the owner then plugs out earlier than expected, and the fleet operator had planned charging after that point in time, the EV may leave with less energy than intended. A risk described by a percentage may be easier to communicate to the EV owner than a more sophisticated expression of the risk/benefit trade-off.

There are numerous ways in which EV owner behavior can be modelled and predicted. These can, however, be kept relatively simple if night charging is the only period considered and mechanisms such as "instant charging" and "minimum range" features are used to handle outliers (e.g. extraordinary mid-night driving needs).

An important issue in relation to data collection and prediction of behavioral patterns, is the protection of EV owner privacy. This have to be dealt with pro-actively by the fleet operator.
5

Control Architecture

This chapter deals with the control architecture as part of the “Supporting informatics” investigations of this thesis. The following publications constitute the core contributions done by the Thesis Author to this area:

B A comparison of electric vehicle integration projects.

C Smartly Charging the Electric Vehicle Fleet.

The publications will be referred to by their letter (B,C) in the following.

5.1 Introduction

When the purpose of controlled charging and the requirements and impacts of key stakeholders have been established, the next task will be to build a suitable control architecture. Choosing the control architecture comes down to deciding what entities will have control over charging, where physically to place the necessary control systems and software logic and finally to establish the, possibly hierarchical, relationship between such systems.

The same aim, for instance smart charging, can be achieved by several different control architectures. There may, however, be differences in what is most practical and efficient to implement. This chapter is the first within the supporting informatics part of this thesis since the choice of control architecture will shape the form of the communication solutions and optimization models to be used. Basically there are two
5. CONTROL ARCHITECTURE

high-level architectures to choose from - Centralized or distributed. These options are shown in figure 5.1

![Figure 5.1: Centralized and distributed architecture](image)

**Figure 5.1: Centralized and distributed architecture** - The high-level architectural options for EV integration.

A centralized architecture is generally characterized by having the control and decision making delegated to a common coordinator and letting each Distributed Energy Resource (DER) be directly controlled by this entity. In contrast, a distributed design means that each DER will act as an independent, intelligent, and autonomous agent that responds according to a set of incentives and information. The above is a coarse-grained distinction and several flavors and variations exist. The centralized approach maps nicely to the Virtual Power Plant (VPP) concept while the distributed approach can be related to the field of agent theory.

Another important aspect is how a resource, in this case an Electric Vehicle (EV), is described to the surrounding world. Another useful distinction can be introduced:

**Structural decomposition** Each detailed component, all measurements and the exact operational state of a unit is communicated to external entities with the proper permissions to receive such information.

**Functional decomposition** Internal details is hidden and the resource is rather described by the functional services that the unit may provide.

The former category fits well with the approach in classical SCADA-like automation approaches as that of IEC 61850 which will be described in the next chapter. The latter
fits with the more autonomous, lowly coupled, approach followed in the service oriented concept seen within contemporary internet use. A final consideration covered by this chapter is what high-level functionalities that should be implemented in the control system after a control architecture has been chosen. In this thesis the centralized control architecture is chosen and the “Thesis work and contributions” section describes why.

5.2 Related Work within Area

One of the largest and first European projects to thoroughly explore the use of the VPP concept was the FENIX project [2]. This project introduced a distinction between a commercial VPP (CVPP) and a technical VPP (TVPP). The commercial version would act on the power market to meet a financial goal. In contrast, the technical version would be used to provide technical services to the grid.

Another thorough study of the VPP concept has been done by Shi in [4]. Shi has focused on another type of the VPP concept - the generic virtual power plant (GVPP). The reason for a VPP being generic is that it would be able to handle and aggregate various types of DERs. As will be done for the EDISON VPP/fleet operator in this chapter, Shi has suggested the generic, high-level functions that would need to be implemented to support the operation of the aggregator. See figure 5.2

For reference, it can be interesting to investigate the control architecture chosen by a set of EV integration projects. This was investigated in core publication B and is illustrated in figure 5.3

As can be seen, both the e-mobility project Berlin and the University Of Delaware (UD) Vehicle-To-Grid (V2G) programme uses partly-centralized approaches. The e-mobility project, like what is the case for UD V2G, lets the EV itself implement software that will dictate the degree to which the EV will participate in intelligent EV utilization concepts.

The UD V2G programme depends on the area of agent theory by defining local software agents (JADE framework) for each device in the system [39] - e.g. an EVSE agent, an EV agent and an aggregator agent. Each of these have distinct and unique objectives and the communication between them is “negotiation-like” in nature. Interestingly, since the implementation is aimed at current markets designs in the PJM area, a number of the responsibilities still have to be left to the aggregator and thus the
5. CONTROL ARCHITECTURE

Figure 5.2: Function-based design for a GVPP - A generic and reusable model that generalizes the objective of the VPPs via a function-based approach. Source: Shi You

Figure 5.3: Comparison of architectures - Architectures chosen in a set of state-of-the-art electric vehicle demonstration projects
solution can be considered a hybrid between the centralized and de-centralized design, i.e., the individual EV agent will be given responsibility of making sure that driving demands are meet - but will depend on the aggregator agent in connecting and adhering to the power market.

5.3 Thesis Work and Contributions

This section presents the architecture chosen as part of the EDISON project and how it was used to implement a EDISON VPP back-end system, used to demonstrate the operation of a fleet operator.

5.3.1 System Architecture of EDISON

In the EDISON project, the choice of control architecture for demonstration software was left to Work Package 3 (WP3) in which the Thesis Author participated. Here the choice became using a centralized design. The main reason being that this approach best suits the current market models and available EV/EV Supply Equipment (EVSE) technology.

The use of agents is projected to allow for a more flexible and dynamic forming of ad-hoc groups of DERs for meeting a broad array of goals (39). It is, however, the opinion of the Thesis Author and the other participants of EDISON WP3, that agent technology may take more years to implement in the power system than is the case of a centralized approach.

EDISON WP3 was inspired by the distinctions made in FENIX between a technical and commercial VPP and therefore explored both options. In the end, the choice fell on the commercial VPP since the market allows for providing technical services to the power system while at the same time releasing a monetary benefit to stakeholders. This also made the implementation easier as the interface to the market is better defined than an interface directly to a system operator would be. The two possible approaches are illustrated in figure 5.4.

Relating the choice of VPP control architecture in EDISON to the variations described by FENIX and Shi, The EDISON VPP then becomes centralized, non-generic (focused on the EV as a resource) and commercial (interface with the market). Again,
it can be argued that participating in present and future ancillary service market products (see market chapter) makes it is less necessary to distinguish between a technical and commercial purpose of a VPP - both would be done at once.

5.3.2 High-level Functions

Having defined the architecture, the focus was then put on the functions needed in the EDISON VPP used by the fleet operator. Figure 5.5 presents such functions.

This functionalities are presented in a book chapter as part of the core publication C The figure conveys that the control system would have to handle the EV fleet as an aggregated group when acting and optimizing toward market players, but will have to take individual considerations into account when managing the charging behavior of individual EVs. This observation has an impact on how to form the optimization problem for the fleet. Another property of the figure is that functionality is divided into three distinct groups. Namely “data”, “analytics”, and “logic”:

- **Data** This group stores previous market prices and fleet behavior on an aggregated
Figure 5.5: High-level centralized fleet operator functionalities - Functions at the individual and aggregated level, subdivided into 'data', 'analytics' and 'logic'
5. CONTROL ARCHITECTURE

level, enabling better forecasting and optimization for acting on the power market.

On an individual level, data is stored that describes the service level agreement between the EDISON VPP and an EV owner, EV hardware specifications and the EV owner’s plug in habits.

Analytics This group covers the mathematical computations necessary to support the logic of the EDISON VPP. Forecasting relies on historical data to predict market prices on an aggregated level which supports better bid strategies. Forecasting also determines future individual EV usage patterns. Optimization is used to minimize charging costs of the EVs on both the aggregated and individual level. The individual optimization is limited by the constraints introduced by the distribution grid, EV specifications and EV owner energy requirements. On the aggregated level, profit maximization can be done when acting on the regulating and reserve markets.

Logic This group defines the main operational goals of the EDISON VPP, namely to act on the power market to generate savings or revenue for itself and its clients, and to intelligently manage the charging behavior of EVs through individually tailored charging schedules.

The demonstration software developed as part of EDISON implements the above functionalities.

5.4 Sub-conclusion

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.

5.4.1 Contributions and Results by the Thesis

The architectural choice in EDISON has been inspired by architectures explored by other research projects and academia. The Thesis Author have participated in building an architecture that is:

- Centralized, and thus depends on an aggregating entity.
- Based on a commercial objective, trading on the market.
• Focused on managing EVs, rather than being generic.

Having established the control architecture, the Thesis Author participated in building a back-end system to demonstrate coordinated charging. To this end the follow was done:

• Necessary functionalities were defined in terms of data, analytics and logic.

• The backend system was developed in code and was used in end-to-end tests in EDISON.

• The developed back-end system facilitated tests of communication, prediction and optimization as well as the EV and EVSE hardware included in the field trails.

5.4.2 Discussion and Recommendations

The EDISON project have identified a centralized approach as the most suitable short-term architecture for EV integration. As the power markets and power system evolves, the attention may be turned to a more decentralized approach, e.g., using software agents.

An interesting aspect of the placement of intelligence and control inside or outside the EV itself, is the approach chosen by car OEMs. OEMs involved in early smart charging schemes such as Nissan and the Daimler group have promoted solutions where the EV is in charge of the charging process. This is not necessarily because the OEMs are strong believers in agent technology but rather because they want to protect the EV and its battery from external mismanagement and at the same time protect the business potential of intelligent charging.

A conclusion drawn from the core publication B, regarding the architecture chosen by different projects is that the placement of control logic and responsibilities between EV, EVSE and aggregator, differs between the integration projects investigated. One key question is how much intelligence will implemented at the EV. If a common architecture is not found, then standardization efforts must respect and manage the resulting diversity.
5. CONTROL ARCHITECTURE
Communication

This chapter deals with communication as part of the “Supporting informatics” investigations of this thesis. The following publications constitute the core contributions done by the Thesis Author to this area:

B A comparison of electric vehicle integration projects.

C Smartly Charging the Electric Vehicle Fleet.

F Facilitating a generic communication interface to distributed energy resources - Mapping IEC 61850 to RESTful Services.

The publications will be referred to by their letter (B,C,F) in the following.

6.1 Introduction

Having established a control architecture, the next question is how to transfer the necessary pieces of information between the control systems in a reliable, robust, secure, and standardized way.

Typically a communication standard consists of the following components:

Data model The formalized description of the structuring and formatting of data.

Protocol mapping The protocols and technologies that are used to transfer the data across a network.
6. COMMUNICATION

Smart grid informatics research has already presented a host of possible communication solutions. Often smart grid integration sub-areas have their own set of communication solutions. Most types of Distributed Energy Resources (DER), for instance, have their own set of standards. Take for instance the IEC 61400-25 communication interface standard for wind power plants, home automation standards such as Open Building Information Xchange (oBIX), AS 4755.3.1-2008 (Air Condition demand response), and the work of the OPEN meter network to standardize smart meter communication. Such standardization efforts are also found within Electric Vehicle (EV) integration.

It can be useful to divide communication standards into a few categories:

Firstly, communication solutions can either be said to be generic or application specific in nature depending on how many scenarios and devices they are designed to cover. New smart grid application areas can either be addressed by extending existing standards or by proposing new ones.

Secondly, as touched upon in chapter five, “Control architecture”, communication standards can either use a structural of functional decomposition of resources, i.e., describe a device in terms of its exact operational parameters and physical components or in terms of the high-level functions and services that it can provide.

In relation to the categories mentioned above, IEC 61850 can be called a generic standard using structural decomposition. It also represent a relatively mature standard and it therefore seems reasonable to investigate its potential in EV integration before suggesting new solutions.

6.2 Related Work within Area

The use of the IEC 61850 standard for substation automation is thoroughly investigated and documented (40, 41). Such publications describe the potential that IEC 61850 has in providing monitoring and control capability of in-field equipment in an interoperable and standardized fashion. Also, the extension of IEC 61850 to applications beyond substations have also been thoroughly researched (42, 43).

As mentioned in the introduction, most communication standards can be described in terms of their data models and protocol mappings.

An investigation regarding the IEC 61850 protocol mapping can be found in (44) by Schmutzler. Here, Schmutzler demonstrates how Devices Profile for Web Services
(DPWS) can be mapped to IEC 61850. DPWS describes how the web service concept, and the WS* technologies behind it, can be used towards embedded devices. Schmutzler have thereby demonstrated how a popular and feature-rich web technology can be applied to IEC 61850 to increase interoperability.

Other research also cover the data description of IEC 61850. In (45), Sui suggests using OPC UA instead of MMS and supplementing the data model of IEC 61850 with OPC UA information modelling. The purpose of applying OPC UA is to promotes DERs as Service Oriented Architecture (SOA) ready devices.

The possibility of extending IEC 61850 standard to many different applications, using different contemporary communication technologies, increases its potential towards EV integration.

In B, a comparison is made between the communication technology solutions chosen by three projects as seen in figure 6.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>EDISON</th>
<th>-MOBILITY</th>
<th>Vehicle to Grid Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication Standards</td>
<td>IEC 61850</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 6.1: Project comparison of communication technologies - Comparison of the communication technologies chosen by three EV integration projects.

The projects all use the internet and the associated TCP/IP stack on the network/transport layer as well as Power Line Communication (PLC) on the physical layer (between EV and EVSE). While the projects are aligned on the lower parts of the OSI stack, they are very divided on the application level protocols. The solutions span from the structural decomposition used by IEC 61850 to the use of agent software. The EDISON project is the only of the investigated projects to use a standardized communication protocol (IEC 61850).

If IEC 61850 is used between fleet operator and EVSE, as described in the following section, there is still a need of communication solutions between EVSE and EV.
Some of the options available for EV to EVSE communication have been investigated in a special project supervised by the Thesis Author. In the project report, Johansen compared the use of Negative Side Signaling (NSS) and PLC for the physical communication layer. The report points to PLC as being the most likely candidate for use in future EV integration. For PLC the main choice is between using wide- or narrow band technologies. HomePlug GP is described as a wideband solution with a data rate of up to 10Mbps. There are some technical (limited range, no support for both DC and AC) and regulatory (reserved frequency bands) limitations on using wideband technologies. One of the main advantages of wideband, however, is a higher data rate compared to narrowband. The rates given by narrowband is sufficient for controlled charging-related communication but may not support additional communication applications, e.g., multimedia. The report also investigates the use of a tentative version of the ISO/IEC 15118-2 standard for the upper communication layers. The use of IEC 15118 and PLC, as part of the EDISON project, is also touched upon in C. The emphasis in the thesis and the following sections is on communication between EVSE and fleet operator.

6.3 Thesis Work and Contributions

This section will describe the Thesis Authors experience with the IEC 61850 standard for the application of EV integration.

6.3.1 Research on the IEC 61850

Figure 6.2 illustrates the main components of IEC 61850 based on the structural decomposition of a Micro Combined Heat and Power Unit (CHP).

The figure includes the reusable “building blocks” of the data model (logical nodes, data sets etc.) and the suggested communication protocol mapping (Manufacturing Message Specification (MMS) on top of the TCP/IP stack using Abstract Communication Service Interface (ASCI) definitions). For a description of the standard refer to core publications C and F.

While working with the standard, the Thesis Author together with co-authors in F have suggested extensions and additions to both the protocol mapping and data model.
6.3 Thesis Work and Contributions

6.3.1.1 Using REST Services

As mentioned above, the IEC 61850 standard initially pointed only to MMS as the recommended application level protocol. While MMS represents a valid choice for IEC 61850 implementation, there are certainly other approaches which can and should be explored.

An obvious candidate is the use of web service technologies, which have seen use in a broad set of domains to promote SOA. Web services represents a well-understood, open, interoperable and feature-rich framework to grant access to information services on the web. Web services have, for instance, seen early support in standards such as 61400-25 for wind power plants.

Web services are often associated with the Simple Object Access Protocol (SOAP). The addition of SOAP based extensions to web services provides a rich list of features and extensions. These features and extensions are captured in a set of specifications referred to as “WS-*”. Instead of focusing on SOAP-based services, however, another alternative exists; REpresentational State Transfer (REST) services. REST services is considered a simpler and more web-centric approach to web services that uses the basic features and methods (GET, POST, PUT and DELETE) of the HTTP protocol.
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In REST a service is accessed as a resource and is “fetched” as you would an HTML page or image, via a URL.

The IEC 61850 reference paths resemble a fully-qualified file-name notation which can be mapped directly to a URL as visualized in figure 6.3.

![Figure 6.3: Mapping to URL path - REST URL to access current charging power of an EV](http://hostname/EV1/MMXU/TotW/mag/f)

REST services are implemented by following a set of principles (Use of HTTP, everything is a resource, etc.) and is not, as SOAP services, a standard.

6.3.1.2 Data Model

To move the IEC 61850 standard beyond the substation environment, an extension called IEC 61850-7-420 was developed to address the integration of DERs into the power system. A new set of logical nodes, one of the main building blocks of the IEC 61850 standard, was introduced to cover the components, measurements and functionalities of such units.

An interesting aspect of using IEC 61850-7-420 was to see how useful these nodes were at representing an EV. The results of the study were that the logical nodes in 7-420 not fully represented the needed values, especially for EV batteries, such as SOC and battery capacity. As a result of this work, two new logical nodes were suggested representing an EVSE (ZCHS) and an EV (ZCEV). These additions have been suggested toward the IEC standardization body for consideration.
6.3 Thesis Work and Contributions

The logical nodes from IEC 61850-7-420 which were used in the implementation, as well as the new ZCEV and ZCHS nodes (Marked with “61850 Extension”), are illustrated in figure 6.3.

![Logical Nodes Diagram](Image)

**Figure 6.4: Logical nodes used in implementation** - List of logical nodes used to represent the EVSE and EV as part of the data model of IEC 61850. *Source: Anders Bro Pedersen.*

6.3.1.3 Test of IEC 61850/REST Implementation

An IEC compliant server have been developed as described in (47) and have been tested in a series of demonstrations towards electric vehicles as part of the EDISON project. The full EDISON communication setup is illustrated by figure 6.5.

The communication setup have been tested towards different brands of EVs in EDISON. Most vehicles were monitored in a read-only fashion while a single vehicle was controlled via IEC 61850 based schedules (“DSCH - Energy and/or Ancillary Services Schedule” and “DSCC - Energy and/or Ancillary Services Schedule Control”). A screenshot from a demonstration with such vehicles can be seen in figure 6.6.
6. COMMUNICATION

Figure 6.5: Communication setup in EDISON - Communication standards used to connect the EV, EVSE and fleet operator.

Figure 6.6: Test of IEC 61850 communication - Use of IEC 61850 towards a vehicle fleet - data such as status and SOC is displayed in a fleet operator interface.
6.4 Sub-conclusion

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.

6.4.1 Contributions and Results by the Thesis

The Thesis Author have contributed to the following activities relating to communication solutions for EV integration:

- IEC 61850 have been evaluated for the application of EV Integration.
- The use of REST services as a protocol mapping for IEC 61850 have been investigated.
- A list of logical node extensions have been suggested as an addition to IEC 61850-7-420 to better represent EVs and EVSEs. They have been sent to IEC WG17 for possible inclusion in an updated version of IEC 61850-7-420.
- The suggested communication setup have been tested in a set of EDISON-related demonstrations.

The communication qualities, focused upon throughout this chapter, have been simplicity and interoperability. Other qualities, such as security and latency, are of course also important and are discussed in the following section.

6.4.2 Discussion and Recommendations

Security is an important topic, both for EV integration and for smart grids in general. A lot of solutions for providing confidentiality, integrity and availability can be provided by “of-the-shelf” technologies already tested in other applications. For the IEC 61850/REST implementation the use of the Transport Layer Security (TLS) as a cryptographic protocol can be used to ensure confidentiality and integrity. This protocol have seen applications in security-critical applications such as web banking.

If using SOAP based web services on top of the IEC 61850 standard, Web Service Security (WS-security) can be used. WS-security describes the use of signed SOAP messages for integrity, encryption in SOAP messages for confidentiality and the use of security tokens for guaranteeing sender identity.
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If MMS is used as the application layer protocol, on top of IEC 61850, a security profile is recommended in the “IEC 62351-4 Security for any profiles including MMS”. The IEC 62351 standard was made specifically to define security for a number of IEC Technical Committee 57 communication standards - including IEC 61850. IEC 62351 also points at TLS as a protocol for providing security.

In general, it is recommended to align EV communication security with smart grid related security standardization work from standards organisations such as IEC (e.g. IEC 62351) and NIST (e.g. “Smart Grid Cyber Security guidelines”).

Latency in communication depends in part on the inevitable delay caused by the use of the internet and the associated routing of data over the nodes in a huge meshed network. Another part is the overhead, in term of size, that the protocols used add to the data packages.

Theoretically, the use of REST should reduce the amount of data to be sent since the overhead of using SOAP is avoided. It is, however, unknown if this makes a measurable difference. Latency in communication have not been a topic of investigation in this thesis, but the following observation can be made; In demonstrations performed over the internet with the IEC 61850/REST stack, data was received within a sub-second time scale. If the application domain is ancillary service market integration (“Market integration” chapter) and the shortest required response time here is 30 seconds (“Primary reserve” and “Frequency controlled disturbance reserve”) then latency is not a problem. In some of the most time-critical intelligent EV integration concepts proposed, the EV would react directly on local measurements of net-frequency, and communication latency would not matter.

There are several other communication issues that should also be considered, among them are scalability, accessibility and firewall traversal. For the latter issues a solution using SIP have been suggested by Jansen in [49]. SIP provides a means for creating a point-to-point connection between clients not accessible through a global fixed IP. For firewall traversal, Session Traversal Utilities for NAT (STUN) and the Traversal Using Relay NAT (TURN) is suggested. This approach is also described in C.

Looking to the future, it is likely that new standards covering EV communication will emerge. This chapter have already touched upon the ISO/IEC 15118 which defines how EV to EVSE communication can be implemented. A protocol possibly rivalling
IEC 61850 for EV use, is the Open Charge Point Protocol (OCPP). Flavours of OCPP is already supported by a series of EVSE vendors.

Communication standards should support as many intelligent EV utilization concepts as possible. For the IEC 61850 implementation described in this chapter this meant adding logical nodes to describe battery SOC and the use of energy Schedules to control charging - this allowed for the concept of smart charging to be realised.

It will be interesting to see if future smart grid standards will be as broad and generic as IEC 61850 or more application specific like IEC 15118 and OCPP. It will also be interesting to see whether structural or functional decompositions will be the norm. It can be argued that the latter is a better match with the SOA paradigm often pursued in modern web implementations.
Optimization

This chapter deals with charging optimization as part of the “Supporting informatics” investigations of this thesis. The following publication constitute the core contributions done by the Thesis Author to this area:

E Prediction and optimization methods for electric vehicle charging schedules in the EDISON project.

The publication will be referred to by the letter (E) in the following.

In addition to the existing publication, new material, mentioned in the sections on markets and stochastic optimization, are presented in this chapter. This work is part of a study attempting to combine real Electric Vehicle (EV) data (new material in chapter four “EV owner”) with stochastic programming (this chapter).

7.1 Introduction

Mathematical optimization is used to make the best possible decisions given a well defined objective and a specific domain. Applied to this domain (intelligent EV integration), objectives can be dictated by the market (chapter two) and the constraints by the distribution grid (chapter three) and the EV owner (chapter four). The transfer of EV owner, grid and market data must be supported by the used control architecture (chapter five) and communication technologies (chapter six).

An important issue is the information on which the optimization will be based. It is necessary to understand what information will be available at each operational stage,
7. OPTIMIZATION

the possible uncertainty of such information and the information “certainty gain” as time progresses.

Chapter three “Grid integration” described how grid capacity information may be made available to the fleet operator and chapter four: “EV owner” described how plug in behavior may be predicted. The latter chapter links directly to this one, by presenting the data which can be used for scenario generation.

The following figure illustrates the approach used in this chapter where predicted or known information is used for defining a suitable charging schedule for an EV. This process could be repeated as new information is made available throughout the operational stage.

![Figure 7.1: Optimization approach](image)

The fleet operator can not avoid individual charging management, due to individual hard constrains, but a possible refinement of the above approach, not explored here, would be to consider the EVs as a fleet until the operational stage.

Using fleet averages on demand and availability may be sufficient for acting on the market since there will be a “smoothing effect” when enough EVs are part of the fleet. This approach would also be computationally less heavy.
7.2 Related Work within Area

Making individual EV schedules during the planning phase, might, on the other hand, yield the most accurate market bids. These issues of individual vs. aggregated portfolio management is briefly discussed in the last section of the chapter, but mostly left to future research.

This chapter will focus on charging cost minimization for a single vehicle considering the access to different markets and uncertainty in plug in, demand and grid capacity.

The mathematical model which will be presented here has been implemented and tested using “General Algebraic Modeling System” (GAMS) software.

7.2 Related Work within Area

In a first wave of research within EV fleet optimization, different combinations of optimization objectives and constraint have been investigated. Two commonly investigated objectives are either the minimization of charging costs or the maximization of the number of EVs the distribution grid can support.

From the former category numerous publications have demonstrated the use of linear optimization for controlled charging. In the paper (50) the authors demonstrate the minimization of charging cost using two different approaches for including battery considerations. One using a quadratic approximation of battery behavior and another using a linear approximation. The authors found that linear approximation sufficiently represents the battery and is much faster to compute than the quadratic approach. In (51), Sundstroem, Corradi and Binding introduces the use of time and energy margins to compensate for prediction errors in plug in duration and energy demand. This is a simple approach for handling stochastic EV owner behavior. In (52) Sundstroem and Binding propose an optimal charging method where the fleet operator is aware of grid constraints. Here, a cost-minimized charging schedule is validated by building a flow network and solving the maximum flow problem.

The above papers have demonstrated that optimization methods can reduce the energy cost for the EV owner and fleet operator while considering several different constraints.

Concerning the objective of maximizing EV grid integration, a publication by Lopes in (53) demonstrates that smart charging, specifically aimed at maximising EV penetration, can successfully increase the number of EVs a distribution grid can support.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_j$</td>
<td>kW</td>
<td>Charging power at level $j$ (only used by binary model)</td>
</tr>
<tr>
<td>$X_{ij}$</td>
<td>0/1</td>
<td>Binary decision variable indicating whether to charge at time interval $t$ at power level $j$ (only used by binary model)</td>
</tr>
<tr>
<td>$d_t$</td>
<td>hour</td>
<td>Duration of time interval $t$</td>
</tr>
<tr>
<td>$p_t$</td>
<td>Euro/kWh</td>
<td>Energy price at time interval $t$</td>
</tr>
<tr>
<td>$c_t$</td>
<td>kW</td>
<td>Charging power at time interval $t$</td>
</tr>
<tr>
<td>$A^{neg}$</td>
<td>Euro</td>
<td>Total cost of buying energy on adjustment market</td>
</tr>
<tr>
<td>$A^{pos}$</td>
<td>Euro</td>
<td>Total income from selling energy on adjustment market</td>
</tr>
<tr>
<td>$B^{neg}$</td>
<td>Euro</td>
<td>Total cost of negative deviations on balancing market</td>
</tr>
<tr>
<td>$B^{pos}$</td>
<td>Euro</td>
<td>Total cost of positive deviations on balancing market</td>
</tr>
<tr>
<td>$P^{neg}$</td>
<td>Euro/kWh</td>
<td>Purchase price of energy on adjustment market</td>
</tr>
<tr>
<td>$P^{pos}$</td>
<td>Euro/kWh</td>
<td>Selling price of energy on adjustment market</td>
</tr>
<tr>
<td>$P^{neg}$</td>
<td>Euro/kWh</td>
<td>Energy price of negative deviations on balancing market</td>
</tr>
<tr>
<td>$P^{pos}$</td>
<td>Euro/kWh</td>
<td>Energy price of positive deviations on balancing market</td>
</tr>
<tr>
<td>$D_w$</td>
<td>kWh</td>
<td>Energy needed for next drive in demand scenario $w$</td>
</tr>
<tr>
<td>$E_{def}$</td>
<td>kWh</td>
<td>Deficit of energy caused by a late plug in, in plug in scenario $v$</td>
</tr>
<tr>
<td>$E_{sur}$</td>
<td>kWh</td>
<td>Surplus of energy that can be sold in adjustment market in plug in scenario $v$ and demand scenario $w$</td>
</tr>
<tr>
<td>$K_{vw}$</td>
<td>kWh</td>
<td>Purchase of extra energy in adjustment market in plug in scenario $v$ and demand scenario $w$</td>
</tr>
<tr>
<td>$F_{def}$</td>
<td>kWh</td>
<td>The energy deficit created by grid congestion</td>
</tr>
</tbody>
</table>

Table 7.1: Symbol overview - Symbols used on the following pages

As more considerations are combined from the market, EV owner and grid, the optimization methods will increase in complexity. This means that they will cover more constraints, multiple objectives and should also deal with uncertainty.

An example of a publication that seeks to bring together several objectives and constraints is (32), again by Binding and Sundstroem. The publication demonstrates an optimization problem where interactions between a Charging Service Provider (CSP), a Distribution System Operator and a Retailer seeks to both follow system-wide energy prices while still adhering to grid constraints.

7.3 Thesis Work and Contributions

7.3.1 Cost Minimization

A first approach to optimization was suggested in core publication E. The approach uses binary programming to decide in which time periods to place charging, based on
an energy demand and known prices. The availability time periods is predicted using exponential smoothing. The objective function is defined as follows:

\[ \text{Min} \sum_{t=1}^{T} \sum_{j=1}^{M} c_j d_t p_t X_{tj} \quad (7.1) \]

Where \( p_t \) is the cost of energy at time interval \( t = 1, \ldots, T \). The length of each time interval is \( d_t \) and \( c_j \) is the charging power used from a set of available levels \( j = 1, \ldots, M \).

In the objective function \( X_{tj} \) is used as the decision variable specifying whether charging should be carried out at time \( t \) with charging level \( j \). The function is then subject to the following constraints:

\[ \sum_{j=1}^{M} X_{1j} \leq 1, \ldots, \sum_{j=1}^{M} X_{Tj} \leq 1 \quad (7.2) \]

\[ \sum_{j=1}^{M} \sum_{t=1}^{T} c_j d_t X_{tj} \geq D \quad (7.3) \]

The first of the constraints \( 7.2 \) states that in all periods, charging can only be carried out using one of the available charging levels. The second constraint \( 7.3 \) is used to satisfy an energy demand \( D \) for the next trip. It could be possible to include grid constraints in terms of charging limits using a matrix \( c \in \mathbb{R}^{T \times M} \) of possible charging powers where each row would be a timeslot and each column a supported charging power.

The above represents a first approach to charging optimization using a deterministic model.

### 7.3.2 Introducing Markets

In this section the above optimization problem is extended to include decision stages where the fleet operator can use markets to meet the energy demand of an EV, while minimizing the cost of charging. The following markets are considered:

**Day-ahead market** Market in which the fleet operator bids on energy before the day of operation.
Intra-day adjustment market

Intra-day market that allows the fleet operator to compensate for positive or negative deviations after the day-ahead market has closed.

The model will include two stages - one for each of the above markets. First the fleet operator will attempt to meet the demand on the day-ahead market based on the predictions on EV owner plug in time, demand and grid capacity. In the second stage, when the actual plug in occurs, the exact demand and plug in time will be known (certainty gain). The fleet operator must then use the adjustment market to compensate for any energy surplus or deficit caused by the uncertainty. A final market - the balancing market - is also included as a way to settle real-time imbalances introduced by the fleet operator. This is not modelled as a stage since it is assumed that there is no recourse for the kind of real-time events that necessitates the use of this market.

The stages are illustrated in figure 7.2. The picture uses the same terminology (planning, scheduling, operation) as was introduced in core publication A regarding the operational stages of a fleet operator.

Figure 7.2: Markets and stages - Use of markets in relation to charging cost minimization for EVs.

The above approach is not meant to accurately reflect the structure and mechanisms for any specific market, but rather illustrate how the use of different sub-markets may influence the optimization done by the fleet operator.
The markets are now introduced to the objective function defined in the previous section. The problem is also changed from being binary (using $X_{tj}$) to linear.

$$
\text{Min} \sum_{t=1}^{T} c_t d_t p_t + A^{neg} - A^{pos} + B^{neg} + B^{pos} \quad (7.4)
$$

In the above $\sum_{t=1}^{T} c_t d_t p_t$ is the cost of energy purchased on the day ahead market and $c_t$, representing the charging power at time period $t$, is the decision variable.

$A^{neg}$ and $A^{pos}$ represents the cost for negative and positive energy deviations which can be handled through the adjustment market. $A^{pos}$ being negative denotes that unused energy can be sold back to the market. It is assumed, however, that a "Two-sided penalty" scheme is used, i.e., buying and selling energy in the adjustment market will always be less advantageous than in the day-ahead market.

Finally $B^{neg}$ and $B^{pos}$ is the cost for handling negative and positive deviations through the balancing market. The prices are assumed to be considerably higher than on the adjustment market and to represent a cost regardless of whether the deviation is positive or negative.

Prices on all markets will be subject to uncertainty and the fleet operator will have to rely on prediction methods in its planning. It has, however, been chosen to leave this out of the model since the emphasis here is on EV owner and grid uncertainty. Price scenarios can, however, be included in the model using the same approach as will be described in the following sections.

Before introducing uncertainty, the fleet operator can avoid both the adjustment and balancing markets. As will be seen in the following, however, uncertainty will make the markets a necessary means for recourse in certain scenarios.

### 7.3.3 Introducing Uncertainty - EV Owner Behavior

The behavioral patterns of EV owners, in term of nightly plug ins, will be subject to uncertainty as shown in chapter four “EV owner”. The two parameters which will be considered here is the time of plug in and the energy demand. The energy demand is the difference between the State-Of-Charge (SOC) seen at plug in and the target SOC for the next trip.

To include uncertainty in the optimization, stochastic programming is applied. Specifically, a two-stage stochastic linear program with recourse is introduced. To this
7. OPTIMIZATION

aim, scenarios for both energy demand and plug in time, are defined with an associated probability for each scenario.

These scenarios are added to the objective function as follows:

\[
\text{Min} \sum_{w=1}^{W} \pi_w \sum_{v=1}^{V} \pi_v \sum_{t=1}^{T} c_t d_t p_t + A_{wv}^{neg} - A_{wv}^{pos} + B_{v}^{pos} \tag{7.5}
\]

In the above, the two summations \( \sum_{w=1}^{W} \) and \( \sum_{v=1}^{V} \) are added and the adjustment and balancing market costs are altered to depend on the scenarios. It is, for this case, assumed that handling negative deviations on the balancing market (\( B_{v}^{neg} \)) can be avoided. For the first summation, \( w \) is a demand scenario with a probability \( \pi_w \). For the second summation, \( v \) is a plug in time scenario with a probability \( \pi_v \). The cost of each scenario is then calculated, weighted based on its probability and summed together to give the expected average cost of the problem.

The cost of using the adjustment and balancing markets are calculated by the following equations. First the energy constraint defined in the first section 7.3 is redefined as follows:

\[
D_w \leq \sum_{t=1}^{T} c_t d_t - E_v^{def} + K_{vw} \tag{7.6}
\]

Here \( \sum_{t=1}^{T} c_t d_t \) is purchased day ahead energy. \( E_v^{def} \) is a possible deficit of energy caused by plug in scenario \( v \). \( K_{vw} \) is extra energy that would have to be purchased depending on the demand \( w \) and plug in scenario \( v \). Finally, \( D_w \) is the energy demand that must be satisfied for demand scenario \( w \).

The energy deficit \( E_v^{def} \) is simply calculated by summing energy for the periods in which energy were purchased, but where the EV has not yet plugged in:

\[
E_v^{def} = \sum_{t=1, a_{vt}=0}^{T} c_t d_t \tag{7.7}
\]

Here \( a_{vt} \) is the availability for the given time period \( t \) and plug in scenario \( v \). Next, the definition of a energy surplus becomes:

\[
E_{vw}^{sur} = \sum_{t=1}^{T} c_t d_t - E_v^{def} + K_{vw}) - D_w \tag{7.8}
\]
7.3 Thesis Work and Contributions

$E_{\text{sur}}$, the purchased energy minus the demand, is then the energy that can be sold on the adjustment market.

Using the above equations the market costs become:

$$A_{wv}^{\text{neg}} = p^{A,\text{neg}} K_{vw}$$  \hspace{1cm} (7.9)

$$A_{wv}^{\text{pos}} = p^{A,\text{pos}} E_{vw}^{\text{sur}}$$  \hspace{1cm} (7.10)

$$B_{v}^{\text{pos}} = p^{B,\text{pos}} E_{v}^{\text{def}}$$  \hspace{1cm} (7.11)

In equation (7.9), (7.10) and (7.11) the market prices ($p^{A,\text{neg}}, p^{A,\text{pos}}, p^{B,\text{pos}}$) are multiplied with the energy deviations found at the time of plug in.

These cost calculations assumes that the fleet operator will be able to use the adjustment market at the 2nd decision stage to compensate for most of the energy deviations caused by the realized scenario for plug in and energy demand. An exception is the positive deviation $E_{v}^{\text{def}}$ caused by energy being purchased in hours prior to plug in. These will have to be handled through the balancing market and thus carries a higher cost.

The above model have been implemented and tested in GAMS. If there is a large probability of a late arrival and high demand, the fleet operator will tend to purchase more energy in the day-ahead market and at a later point during the night, to avoid adjustment and balancing market costs.

### 7.3.4 Introducing Uncertainty - Grid Constraints

Grid constraints were discussed in chapter three “Grid integration” and it was argued that certain strategies could be used to provide the fleet operator with knowledge on available capacity in the planning phase. This section describes how grid constraints may influence the cost of charging.

In the following, grid constraints is defined as a reduction of the available active power during one or more time periods due to congestion.

If the fleet operator has knowledge on grid constraints at the time of day-ahead energy bids and purchases, then deviation costs can be avoided. The cost of charging
may, however, still increase if the constraints means that the fleet operator is unable to utilize certain, low-price, periods.

If the grid constraints are only revealed during the operational phase, then the fleet operator will most likely attempt to predict the periods where such constraints may occur. These predictions can, as was done for the plug in uncertainty, be used to generate a set of scenarios. The objective function defined in the previous section 7.3 becomes:

\[
\min \sum_{w=1}^{W} \pi_w \sum_{v=1}^{V} \pi_v \sum_{o=1}^{O} \pi_o \sum_{t=1}^{T} c_t d_t p_t + A^\text{neg}_{wv} - A^\text{pos}_{wv} + B^\text{pos}_{vo} + B^\text{neg}_o
\]

In 7.12 the summation \(\sum_{o=1}^{O}\) is added and the balancing market costs have been altered.

\(o\) is a scenario for grid congestion with probability \(\pi_o\). It can be seen that grid constraints may incur additional costs in the balancing market for both positive and negative deviations (\(B^\text{pos}_{vo}\) and \(B^\text{neg}_o\)).

The following equation defines the energy deviation created by grid congestion:

\[
F^\text{def}_{vo} = \sum_{t=1,a_vt=1,c_{vt}=0}^{T} c_t d_t
\]

The above sums up the contracted energy in hours where the EV is plugged in (available \(a_vt = 1\)) but can not charge due to a charging constraint (constraint \(c_{vt} = 0\)).

The balancing market costs can now be expressed as:

\[
B^\text{pos}_v = p^B,\text{pos} (E_v^\text{def} + F^\text{def}_{vo})
\]

\[
B^\text{neg}_v = p^B,\text{neg} \times F^\text{def}_{vo}
\]

The above equations, 7.14 and 7.15, assumes that deviations caused by charging constraints can not be handled through the adjustment market but must be handled using the balancing market. The positive deviation caused by not being able to charge due to grid constraints are added to the positive deviation created by late plug ins in 7.14. It is assumed that the energy missing from the battery, due to grid constraints,
would still be needed and that the balancing market is used for such unplanned charging.

The above model have been simplified in that the costs of charging constraints only applies to energy bought in the day ahead market, not the energy bought and sold in the adjustment market.

The above grid constraint scenarios have been implemented in GAMS. High balancing costs will generally keep the fleet operator from purchasing energy in hours where there is a risk of grid congestion.

7.4 Sub-conclusions

The following sections concludes this chapter by presenting and discussing results and by giving recommendations on future work.

7.4.1 Contributions and Results by the Thesis

This chapter have described the use of optimization methods to minimize charging costs for a fleet operator. It have been shown that:

- A binary optimization method can be used to minimize charging costs for EV charging.

- Markets and stages can be introduced as a means for deviation recourse.

- EV owner-related uncertainty in terms of time of plug in and energy demand can be managed using stochastic optimization with recourse.

- Scenarios for grid constraints can be included in the model.

The following have been done to implement and test the methods:

- In the EDISON fleet operator software, the binary optimisation method was implemented via Microsoft Solver Foundation (MSF).

- The stochastic version of the optimisation problem have been implemented and tested in GAMS.
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7.4.2 Discussion and Recommendations

The fleet operator will always have to manage charging based on individual and hard constraints, and initial methods have therefore been formulated for a single vehicle. There are, however, certain differences when considering an entire fleet. Energy deviations can, for instance, be balanced out via running adjustments and rescheduling for a larger group of EVs. Advanced portfolio management, and the real-time relationship between individual and fleet level operations by a fleet operator, will be the subject of further studies.

The stages presented here are rather course-grained and the fleet operator will most likely include many more stages. Rescheduling and adjustments could be done every 15 minutes and/or at certain events. A scenario could be that if a specific vehicle have not plugged in at 5 PM, the fleet operator would, according to its probability scenarios, not expect the vehicle to plug in before 10 pm. Replanning could then be done at 5 PM rather than waiting until the plug in occurs as is done in the above model.

The model reflects that grid uncertainty would incur a higher cost than EV owner uncertainty. This is because most EV owner-related uncertainty is resolved at the time of plug in, while grid constraints may occur throughout the entire operational stage. Also, all deviations caused by grid constrains may have to be settled via the balancing market.

Future extensions to the proposed model could be the addition of more constraints, e.g. battery, and uncertainties, e.g. price. Finally it may also be desirable to extend the planning period to cover a longer period e.g. an entire week. This may better incorporate variable patterns in EV owner behavior and market costs.
8

Conclusions

This chapter will summarize the results of each of the two parts of this thesis; Domain interfaces and supporting informatics. Finally, it will be illustrated how the topics investigated in the first part relate to the topics of the second part.

8.1 Domain Interfaces

The chapters, part of the domain interfaces investigation, have sought to uncover the objectives and requirements of the three key stakeholders - market, distribution grid, and Electric Vehicle (EV) owner. The chapters also demonstrate how such considerations will impact the informatics solutions for intelligent EV integration. Results for each stakeholder is covered in the following.

Market Integration

First, EV integration towards the existing spot market was investigated. Demonstration software was developed that showed that EVs could be charged in correspondence with energy prices from the spot day-ahead market. Next, ancillary service markets were investigated in a comparative study between ENTSO-E and American PJM mar-
8. CONCLUSIONS

The outcome of this study was recommendations on EV Ancillary Service (A/S) market integration and a set of proof-of-concept tests.

This study has shown that both the day-ahead energy markets and ancillary service markets are possible targets for EV market integration.

It is recommended to pursue the market products (existing and new) that can best match and reward the EV’s potential as a fast-response high power resource. Charging in correspondence with dynamic energy prices may represent the low-hanging fruit and the short-term aim of EV market integration. More advanced uses, including A/S market participation, can both increase the complexity, but also the potential value. Impacts on battery lifetime must be included in the equation for A/S provision.

Future research should focus on new markets and the best possible utilization of EVs in the power system.

Grid Integration

The Thesis Author has sought to understand how grid congestion may influence the operation of a fleet operator. A set of grid congestion mitigation strategies have been suggested and evaluated in terms of complexity, risk and value. Operation maps with functional stages have been employed as a tool to analyze the tasks and possible stakeholder interactions that each strategy would entail.

The study has revealed the necessity of understanding and harmonizing the objectives and operational tasks of stakeholders that would directly be impacted by controlled EV charging. Early coordination of grid capacity sharing is found to benefit both a fleet operator and the distribution system operator, and would better allow EV participation in system-wide services.

It is recommend to consider whether the future distribution grid should be extended to a degree where it can support charging schemes which would cluster charging in time. This is a trade-off between the value of allowing EVs to target system-wide needs and the value in reducing the need of local grid reinforcement.

Future research should continue to target grid congestion mitigation and the impact congestion will have on the overall use of EVs in the power system.
8.1 Domain Interfaces

**EV Owner**

The Thesis Author has concentrated on plug in behavior and its impact on the flexibility of controlled charging. First, a set of internal combustion engine vehicle data was used to show how a prediction could be performed as input to an optimization method. This approach was implemented and tested as part of the EDISON project. Next, attention was given to a set of real EV driving data, and some early investigations of plug in behavior, including the impact of seasonal changes and driver familiarization, were conducted.

The study revealed a high degree of flexibility for the EVs and owners investigated; the plug in periods were rather deterministic and stretched over long periods of time compared to the energy demand they had to fulfil. The study has also hinted at some of the external stimuli that this flexibility may be used towards. The results of the EV owner plug in behavior investigation can be seen as an input to the optimization chapter where historic data can be used to generate scenarios for stochastic programming.

The Thesis Author recommends using the analytic capabilities of a back end system to predict and utilize the flexibility of an EV. This will strengthen the EV’s value as a resource and can help reduce the required involvement of the EV owner as long as some clear frame conditions for controlled charging are made. A benefit/risk trade-off must be understood and accepted by the EV owner. The risk can be based on the empirical distribution of plug outs and energy demand while the benefit depends on the target of controlled charging.

Future research for the Thesis Author will include a more comprehensive investigation on the Test-An-EV data. A better understanding of plug in behavior is key in understanding the EV’s potential in the future power grid.
8. CONCLUSIONS

8.2 Supporting Informatics

The chapters part of the supporting informatics investigation are influenced by what was found in the domain integration study. The findings are summarized in the following:

**Control Architecture**

Based on studies of the virtual power plant concept, a centralized, commercial, EV specific architecture was defined. Next, the functionalities that should be part of such a platform were specified. Finally, the architecture and functionalities were implemented in code and used in the demonstration of EV fleet management.

The architecture chosen is meant to reflect a viable and readily implementable way of interfacing an EV fleet with the market. The architecture developed is largely similar to a set of other large EV integration research projects investigated by the Thesis Author. It is concluded that the suggested architecture is well suited to facilitate EV integration.

It is recommended that original equipment manufacturers and fleet operators come together in standardization to establish what systems and entities should be allowed to influence charging. It can be recommended to focus on centralized control short-term and then move towards a more decentralized scheme as research in this area matures.

Future research could focus on combinations of centralized and decentralized control and establish where controlling logic is best placed.

**Communication**

In this study IEC 61850 was investigated in regards to EV integration. It was suggested to extend the IEC 61850 mapping with representational state transfer services for increased simplicity and interoperability. For the data model a new set of logical nodes was suggested to better accommodate EV and EV supply equipment hardware.
8.2 Supporting Informatics

These nodes have been sent to IEC for consideration. The IEC 61850 with REST communication scheme have been implemented and tested as part of EDISON.

The study revealed that using the IEC 61850 standard is a valid option for monitoring and controlling the charging of an EV. There are, however, a number of competing standards which could challenge the use of IEC 61850.

The main recommendation is to use a standard that will not limit the use of the EV in present or future scenarios. This means defining a broad and flexible information model which will facilitate the necessary information and control. The standards also have to meet certain requirements on security which can be ensured by using the right protocols and following standardized security profiles.

Academia should follow standardization to ensure the continued support of future smart grid concepts. It is also recommended to start the transition from the original top-down SCADA approach to a service oriented architecture for EV integration.

Optimization

It was shown how optimization can be used as a tool to reduce the cost of charging. First, a simple binary optimization method was proposed. Then the model was extended to include markets and the use of two-stage stochastic programming to include uncertainty in regards to both EV owner plug in behavior and grid capacity.

The study showed how several constraints and considerations can be combined in an optimization model and how uncertainty can be included in the form of scenarios as part of stochastic programming. The model also illustrated that uncertainty in the distribution grid and EV owner behavior can have an adverse effect on charging cost minimization.

One of the main recommendations is to make optimization models that includes as broad a set of stakeholder considerations as possible.

Future research by the author will extend the model with more constraints and extend the use of stochastic programming. The continued examination of real EV data can help shape and test future models.
8.3 Intelligent EV Integration - Closing Remarks

The following figure \textit{8.1} illustrates the relationship between the chapter topics of this thesis. More specifically it shows how findings and conclusions of initial chapters have been picked up and reflected in later chapters.

![Figure 8.1: Chapter topic relationships - Illustration of how information and choices from the domain investigations map into the informatics chapters](image)

The above figure, along with the findings described above, have shown how the two objectives of this thesis have been fulfilled by conducting a thorough domain investigation and by identifying suitable informatics solutions.

It is hoped that the findings presented, both concerning stakeholders and solution technologies, can be used to release the potential of EVs and promote and support the intelligent integration of EVs into society.
Core publications
A Coordination Strategies for Distribution Grid Congestion Management in a Multi-Actor, Multi-Objective Setting

This paper has been accepted for publication as part of the 3rd IEEE PES Innovative Smart Grid Technologies, 2012, Berlin.
Coordination Strategies for Distribution Grid Congestion Management in a Multi-Actor, Multi-Objective Setting

Peter Bach Andersen, Junjie Hu, Kai Heussen

Abstract—It is well understood that the electric vehicle as a distributed energy resource can provide valuable services to the power system. Such services, however, would have to co-exist with hard constraints imposed by EV user demands and distribution grid operation constraints. This paper aims to address the interactions between the stakeholders involved, mainly considering the distribution grid congestion problem, and conceptualize several approaches by which their diverse, potentially conflicting, objectives can be coordinated. A key aspect to be considered is the relationship between the operational planning and the handling of real-time events for reliable grid operation. This paper presents an analysis of key stakeholders in terms of their objectives and key operations. Three potential strategies for congestion management are presented and evaluated based on their complexity of implementation, the value and benefits they can offer as well as possible drawbacks and risks.

Index Terms—Electric vehicle integration, Distribution grid, Congestion management, Smart charging

I. INTRODUCTION

Grid integration of electric vehicles, distributed generation, and other distributed resources has been a driver for a range of smart grid research activities. Here, the field of intelligent electric vehicle (EV) integration is aimed at minimizing the adverse effects of introducing electric vehicles into the power system and maximizing the value for EV owners, the power system, and society as a whole.

A large part of intelligent EV integration research has been aimed at such topics as optimal charging of electric vehicles in term of charging cost [1]–[3], enabling renewable energy [4]–[6] as well as providing ancillary service to the power system [1], [7]–[9]. Such studies have primarily been aimed at system-wide power services and energy markets while not considering the distribution network. Concurrently, studies have been carried out that look at charging management solely for the purpose of avoiding distribution level grid congestion [10]–[14].

Lately, research done in [15], [16] have been striving to coordinate these objectives, i.e., to optimize the utilization of electric vehicles while still respecting the hard constraints imposed by consumers’ needs and distribution operation constraints. In [15], a conceptual framework consisting of both the technical grid operation and a market environment was proposed to integrate EVs, the activities of all the actors including fleet operator (FO), distribution system operator (DSO) and consumers are described and the simulation results indicate that smart charging can maximize the EV penetration without exceeding grid constraints. However, further research on the coordination between FO and DSO and the interaction between FOs and consumers are not addressed clearly. A further development can be seen in [16], in which a complex scheduling problem involving consumer, fleet operator and DSO were analyzed. The results shows that both power and voltage constraints due to electric vehicle charging can be avoided while the FO and consumer can achieve the objective of minimizing charging costs and fulfilling the driving requirements. This approach requires a somewhat complex coordination between DSO and FO but can potentially deliver a very good solution in terms of optimal grid utilization and safety.

This paper aims to add to the existing research by addressing the interactions between the various actors and conceptualize several approaches, by which their diverse, potentially conflicting, objectives can be coordinated with respect to the operational constraints of the low voltage distribution grid. A key aspect to be considered is the relationship between the operational planning done by the actors and the handling of real time events which is vital for the DSO and the distribution grid that it represents.

While this paper focuses specifically on the case of EV integration, the coordination strategies presented, aiming at congestion management in general, can to a large extend be translated to a more generic demand side management perspective.

The remainder of this paper is organized as follows: Sections II presents three key stakeholders along with their objectives and operational tasks. In Section III a full map of the operations identified is presented and Section IV then expends the map in the examination of three different coordination strategies. Finally, key contributions are summarized and discussed in Section V.

II. ACTORS: OBJECTIVES AND OPERATIONAL TASKS

An overview of the actors, the grid and the main control operations is presented in Figure 1. The figure conveys how the actors’ operations are coupled through interactions via a) a common physical infrastructure, b) control relations and c) other information exchange. The coordination of these operations needs to reflect each actor’s objectives as well
as operational constraints. In this problem formulation, we focus on describing the following key stakeholders and their objectives:
- Distribution System Operator (DSO),
- Fleet Operators (FO),
- Customers (controllable loads / EVs).

Other relevant influencers include the transmission system operator (TSO), other market actors and conventional demand. Their influence is conveyed via control signals, market prices, and physical network utilization, respectively. They do not have to be considered here explicitly as their role with respect to the distribution level is encapsulated via the DSO and FO.

In the following, these key actors are described in terms of objectives and the operations performed to satisfy these objectives.

A. Distribution System Operator

The main purpose of the distribution grid is to enable reliable power delivery to customers at a low-voltage level. Grid operation by the DSO is therefore aimed at effectively balancing two main objectives a) reliable grid operation and b) low cost of operation. We identify the following value drivers for a DSO:

1) Grid component investments,
2) Capacity utilization factor,
3) Component lifetime,
4) Operation cost (incl. resistive losses),
5) Instrumentation and automation efforts.

Provisioning of distribution grid transfer capacity is planned to be sufficient in all cases, that is, capacity is provided by the standard of annual peaks, plus safety factors for anticipated demand increases. In practice this means that distribution grids tend to have a relatively low utilization factor. On the other hand, the distribution grid planners calculate with a high ‘diversity factor’: it could be safely expected that due to the independent nature of most electricity consumption would lead to a smoothing effect that would reduce the absolute peak. As a result, secondary transformers in the distribution grids can be expected to be dimensioned at lower capacity than the total current capacity of all connected households.

The operating state of the distribution grid is limited by the following operation constraints:
- Voltage limits (voltage quality),
- Thermal limits of cables & transformers,
- MVar bands (interface to TSO), or
- Protection settings.

In this paper the focus is on the distribution grid’s ability to transfer active power.

1) Congestion management: The term ‘congestion’ in distribution grids refers to a situation in which the demand for active power transfer exceeds the transfer capability of the grid. As the electricity grid cannot physically get congested, the term subsumes the complex mapping of the above mentioned grid constraints to the network active power transfer capacity as seen for each connection point and the need for deferring demand (or generation\(^1\)). Whereas the constraints listed above are specified in terms of limits for specific parameters (voltage, current, reactive power, active power), they all may influence the active power transfer capability available at a connection point. Their mapping is non-trivial, as it depends on properties of the physical infrastructure, characteristics of consumption devices and built-in control behaviours required by the respective grid code.

In general, the term ‘congestion mitigation’ can then be associated with two types of strategies: a) to (locally) increase the transfer capacity by means of reactive power and voltage control and b) by coordinating the throughput via deferral or curtailment of demand [17]. Both strategies aim at increasing the utilization factor of the distribution grid.

Here, the term ‘congestion management’ explicitly refers to strategies of type b), which aim at the coordination of active power demand with respect to congested grid locations. It can be assumed that available strategies of type a) will be exhausted before type b) strategies are applied. Building on the proposal in [17], the base case for congestion mitigation will be considered active power curtailment.

2) Distribution System Operation Today: DSO tasks in conventional system operation, are mostly focused on ‘off-line’ tasks related to asset management and maintenance. Distribution systems today tend to be weakly monitored as compared to transmission grids, and controlled in a decentralized fashion on the basis of preconfigured local controls (e.g. by means of grid codes and protection settings). Supervisory control is then reduced time-of-day controlled adaptation of control settings, configuration management in response to outages and maintenance related challenges.

Key Operations:
- Grid dimensioning (incl. contingency planning and load curve estimation),

\(^1\)For the remainder of this paper, the perspective of distributed generation is implied.
3) Operations in active distribution grids: To illustrate a future operation scenario with a higher level of automation, it is considered how the above operations can be extended with additional online- and data intensive operations. In order to identify and solve congestion problems, the DSO requires additional measurement equipment and/or technology enabling the anticipation of load patterns and grid ‘bottlenecks’.

Key Operations for DSO congestion management in ‘advanced’ distribution grids:
- Demand forecasting
- Grid state estimation
- Online grid measurements
- Real-time intervention in case of unexpected deviations challenging grid reliability
- Meter data collection and aggregation economically and reliably and shows a relation between VPPs and DSO. In this control system, several families are supplied under one feeder and they own controllable devices, i.e., electric vehicles, besides some conventional load, such as light, TV etc. For these controllable devices, they are divided into two groups according to the method controlled by the VPP, one group is directly controlled by the VPP, which means an extra cards or relays are installed on the user’s device, and the VPP can turn on/off the devices; another group is controlled by price, in which the devices are assumed to be price-responsive. VPP starts to make an energy schedule for its customers with the purpose of minimizing the electricity cost and meanwhile fulfilling their requirement. This problem can be formulated as a linear programming or dynamical programming way [1], [2]. The congestion problem may first happened during the scheduling making, this problem should be solved by the coordination between DSO and VPPs. After the charging schedule was set up, ideally, the users are expected to totally follow the schedule. However, in general, deviation may happen. With the purpose of avoiding the possible congestion (happened again in real time), DSO will monitor the system’s operation conditions dynamically and coordinate with VPPs. The following subsection will discuss the mechanism of solving these congestion problems.

B. Fleet Operators

The fleet operator (FO) is a commercial entity that aggregates a group of EVs in order to actively integrate them into the power market, and in so doing, utilizing their charging flexibility to meet a financial goal. The financial goal could be to achieve savings on the purchase of energy or make earnings by selling ancillary service products or, possibly, a combination of the two.

A FO follows the concept of a ‘virtual Power Plant’ which was first introduced to allow market participation for distributed energy resources.

In the current European power and energy markets, the FO could be a retailer with either a load balance or production balance responsibility, depending on the market/service that the FO would address.

The value drivers for a FO are:
1) Maximize profits or minimize costs by participating in markets.
2) Providing services (cost reductions, convenience etc.) that will attract EV owners as customers.

Due to the participation in markets and customer services, the FO is subject to operating constraints defined by contractual commitments:
- Market schedule (energy/h)
- Customer demand (driving needs)
- TSO driven ancillary service requirements (e.g. reserve capacity)

How the economic value obtained through the market is shared with the customers would be business case specific to the FO. It is also assumed that the FO would maintain a Service Level Agreement (SLA) with its customers that would dictate the degree to which it may control and manipulate the EV charging patterns to achieve goals other than customer driving. This would represent a trade-off between energy savings and EV driving availability that should be understood and accepted by the customer.

The operations of the fleet operator can be divided into fleet level operations and individual level operations as follows.

Fleet level:
- Selection of market products and services
- Contracting
- Market/service forecasting

Individual level:
- Customer SLA management
- Driving pattern prediction

C. Customers

The customers, here EV owners and drivers, are not assumed to be particularly interested in grid issues. Their main value drivers are expected to be:
1) Availability of EV for driving
2) Total cost of ownership/energy

It is assumed here, that the customer will opt for convenience and delegate most of the charging control to the FO. The customer is expected to rely on the frame conditions expressed in the SLA for the daily charging management for ‘typical’ and predictable driving patterns. An optional feature would be to let the customer communicate his or hers exact driving intentions to the FO. This would strengthen the FO ability to utilize the specific EV’s flexibility. The main operations of the customer, besides transportation, would then be:
- Accept, and possibly modify, the SLA with the FO.
- Inform the FO of any non-typical driving needs.

III. MAP OF OPERATIONS

The operations outlined above will in this section be mapped graphically to enable an analysis of different coordination strategies.

- Maintenance and outage related topology reconfiguration,
- Adjustment of transformer taps,
- Fuses and relay operation,
- Fault-analysis and repair.

- Market schedule (energy/h)
- Customer demand (driving needs)
- TSO driven ancillary service requirements (e.g. reserve capacity)

- Meter data collection and aggregation economically and reliably and shows a relation between VPPs and DSO. In this control system, several families are supplied under one feeder and they own controllable devices, i.e., electric vehicles, besides some conventional load, such as light, TV etc. For these controllable devices, they are divided into two groups according to the method controlled by the VPP, one group is directly controlled by the VPP, which means an extra cards or relays are installed on the user’s device, and the VPP can turn on/off the devices; another group is controlled by price, in which the devices are assumed to be price-responsive. VPP starts to make an energy schedule for its customers with the purpose of minimizing the electricity cost and meanwhile fulfilling their requirement. This problem can be formulated as a linear programming or dynamical programming way [1], [2]. The congestion problem may first happened during the scheduling making, this problem should be solved by the coordination between DSO and VPPs. After the charging schedule was set up, ideally, the users are expected to totally follow the schedule. However, in general, deviation may happen. With the purpose of avoiding the possible congestion (happened again in real time), DSO will monitor the system’s operation conditions dynamically and coordinate with VPPs. The following subsection will discuss the mechanism of solving these congestion problems.

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III. MAP OF OPERATIONS

The operations outlined above will in this section be mapped graphically to enable an analysis of different coordination strategies.
A. Analysis Framework

In this section a classification approach is introduced, based on the understanding that the coordination approach is both an automation problem and a market design problem.

A widely accepted hierarchical decomposition of process control into four functional levels describes integrated industrial automation [18]:

- Level 4: plant(s) management
- Level 3: production scheduling and control
- Level 2: plant supervisory control
- Level 1: direct process control

This level-hierarchy is associated with several characterizing parameters, including e.g. time scale, time resolution, planning horizon, and hierarchical dependency of objectives. No single one of these parameters can be considered directly decisive for forming the levels, but together they generate the need for distinguishing qualitatively different levels of automation. The hierarchical dependency of objectives, i.e. that one level is higher and another is lower in ordering, is associated with the means-ends structure of objectives: A higher-level objective is broader in scope and more closely associated with the business objectives of the respective process, and thus ‘higher’ in the value chain; a lower-level objective, in contrast, is there to support and enable other process functions.

In the present multi-actor, multi-objective setting, the single hierarchy does not hold: different actors have different objectives, and yet they must interact with respect to the same process. The present means-ends perspective shall be stripped from the automation hierarchy, to allow for a high-level map of operations. Key elements to be captured in the new map are:

- Key operations and their allocation to actors
- The association of operations with a time scale including a distinction of operational and administrative functions
- The possibility to map interaction sequences between operations

Removing the means-ends interaction sequences between operations at each level, we are left with a mostly time-driven decomposition. We consider the following fundamental stages:

I. Offline Planning
II. Online Scheduling
III. Real-time Operation (Execution)
IV. Offline Settlement

These stages model a logical sequence: each stage is based on a completion of the previous stage. The timing aspect is not essential here as certain types of operation can be performed faster with improved technology. The stages are characterized in the following:

Settlement is about the aftermath: recordings (measurements, sent commands, etc.) of executed operations are consolidated and (financial) responsibility is allocated. The operation stage is about pure execution in real-time. Plans are only executed, and unplanned events occur and physical as well as automatic controls respond without deliberation. The ‘online’ scheduling stage can in time be closely coupled with operation (e.g. reactive scheduling with a 5min resolution) or extend hours or days ahead of it. Scheduling is the stage in which available resources are best known and the platform for execution is to be prepared. Finally, the first stage, here called ‘planning’ has been distinguished from scheduling in the same fashion as unit commitment is distinguished from dispatch: Depending on the specific coordination strategy, we distinguish operations that can be coordinated in an ad-hoc fashion and those that provide the basis for such ad-hoc decisions. Due to these clear distinctions, the framework supports the discussion of interactions between key operation tasks for cross-stakeholder coordination for the complete process. As the operations can be associated with operation objectives of
the respective stakeholder, this map allows for an analysis of the incorporation of the respective value drivers by a given coordination strategy. This ‘horizontal’ level means that the operations have to be considered at the same level of abstraction. A ‘vertical’ perspective would unfold more details of the operations, eventually also revealing physical interactions [19]. The goal is to analyze the benefits and trade-offs involved in specific coordination strategies. Value is hereby understood in a generic sense as to contribution to a stakeholder’s objectives. Given the Operation-Stakeholder allocation and the analysis of value drivers, a similar framework can be employed to also analyse value-network constellations, as exemplified in [20]. However, that type of analysis is beyond the scope of this paper.

B. Base Case Map

To establish a firm foundation for the analysis of different market-based coordination strategies, we identify a base case with a minimum set of operations that will be common to all considered congestion-coordination strategies (Figure 2). This base-case maps out the operations DSO, FO and EV owner would be required to execute in either of the coordinated congestion management schemes.

The base case uses the following assumptions:
- As discussed in [15] and [19], the introduction of controllable demand with significant power capacity such as that of electric vehicles implies a significant risk for distribution assets. To avoid potentially harmful charging configurations, we include the concept of an ‘emergency brake’ in all EV charging post: it enables the unconditional interruption of EV charging on request by the DSO. It could be implemented on the basis of a ‘keep-alive’ signal, the failure of which would immediately interrupt the EV charging process.
- The maps allocate all optimization and coordination intelligence to the FO. It is understood that many of the operations could be implemented using distributed algorithms e.g. in the electric car or charging post.
- Vehicle-to-Grid (V2G) is not considered in this publication. The technology’s potential for congestion relief and its impact on power quality are, however, relevant for congestion management and should be further addressed in future publications.

IV. Coordination Strategies for Congestion Management

Approaches to the congestion problem are outlined and then classified and analysed using the map described in the previous section. All three strategies represent very new approaches to distribution grid congestion management and none of them have been investigated in very great detail.

The strategies investigated are:
- Distribution grid capacity market
- Advance capacity allocation
- Dynamic grid tariff

For each approach a new map is drawn where operations required specifically for the strategy in question are presented in bold. Shared supporting operations beyond the main trace of operations have been omitted for compactness.

To describe how technically and administratively demanding it would be for a DSO or FO to implement and operate the new procedures required by the coordination strategy the parameter complexity is used. A second parameter value denotes the degree to which the strategy would help the stakeholder achieve its operational goal. Finally, the parameter risk describes potential problems associated with the respective strategy in context of a currently uncertain external environment.

A. Distribution grid capacity market

As proposed in [21], this strategy would require a new market for trading distribution grid capacity. For this paper the term ‘Distribution Grid Capacity Market’ is used; Also a new role ‘market operator’ is introduced which is responsible for market operation. The FO will submit requests for their ‘aggregated schedule’ consisting of their scheduled consumption for each node (aggregated capacity), in response they will receive a price for each node, reflecting the respective congestion, and are requested to update their charging schedules. The process is iterated until all constraints are satisfied. The concept used in this strategy can be found in a similar form for the power transmission system [22].

1) Operation sequence:
- First, the FO will make an aggregated energy schedule for EV owners based on its objectives. Afterwards, this aggregated schedule will be sent to the market operator.
- The Market operator will generate a price for the grid capacity according to the schedules. This price is associated with the power difference between the sum of scheduled power and upper power limits of the grid.
- FOs would inform the market operator of their new energy schedule under the initial price. The schedule can be calculated based on the marginal value of a utility function, e.g., cost function in term of the power deviation or satisfaction degree with the ‘preference difference’ (the difference between energy schedule after congestion management and energy schedule before congestion management).
- The market operator then determines whether the distribution grid is overloaded or underutilized and comes up with a new corresponding price. After a certain number
of iterations, the price will eventually converge and accepted by all FOs, which establishes a binding charging schedule.

2) Evaluation: Complexity:
With this strategy, a new market is required which means that the corresponding platform for trading grid capacity needs to be designed and implemented. Also, new communication flows are needed to support the market operations. The market itself will be rather complex to establish and operate.

A lot of complexity is transfered from DSO to the capacity market. Here the DSO will be required to provide the measured and estimated power information to the market operator. The FOs will take on the task of trading capacity and rescheduling the energy consumptions for their customers etc..

Value: With this new market, FOs will have more flexibility to trade and utilize the grid capacity of a distribution system. If the market and capacity information is reliable and well-designed it will ease the operation of the DSO, enable a comparatively high utilization factor and reliable schedules for FOs as well. A further benefit is that no actual consumption information is revealed to other market parties, as only a common congestion price is established per node.

Risk: It must be guaranteed that all FOs adhere to the rules of the market. Another risk lies in the algorithms used to arrive at prices based on utility functions i.e. the computational requirements and time needed for a solution to converge.

B. Advance Capacity Allocation

The simple concept behind this strategy is that the DSO could identify and pre-allocate available capacity by defining a conservative static capacity limit (kW) for each feeder-line based on the capacity rating of the respective transformers and cables and the expected conventional load curves. The EV-equipped households attached to a certain feeder-line would then be given a certain share of available capacity which would be allocated to the FO representing them. To avoid inefficient utilization of available grid capacity due to unused capacity shares, a second step is added to the strategy where FOs can trade their allocated capacity in an over-the-counter manner.

1) Operation sequence:
- The ‘Contracting for capacity sharing’ operation would involve letting the DSO know the mapping between grid connected EV-equipped customers and FOs and then determining how capacity is shared.
- During the scheduling stage, the DSO would use grid load forecasting estimate the available capacity and communicate this to the FOs as defined in the contracts established in the planning stage. After having received its share, the FO could then optionally engage in capacity trading with other FOs operating on the same feeder.
- The DSO should be informed of the bilateral capacity trading so that, in case of violations (i.e. total load observed from EV charging in specific part of grid exceeds sum of allocated shares) penalties for violations can be appropriately placed at the responsible FO.
- Finally the strategy would involve settlement both between DSO and the individual FO and possibly an internal settlement between the FOs that engaged in the bilateral trade.

2) Evaluation: Complexity: Here, rather than dimensioning the physical characteristics of the grid depending on load profiles and simultaneity factors, the DSO would limit the controllable load based on the physical characteristics of the grid. In addition to the location-based grid capacity the DSO would also need to map each grid customers endpoint to an associated FO. There is also some complexity in how the FOs will trade capacity internally and how violations of grid capacity will be dealt with in the settlement stage when trading has been involved.

Value: This strategy represents a rather simple coordination mechanism between FOs and DSOS. The DSO is only required to communicate a single value (capacity) to each FO and is then removed from the equation until the settlement stage. This will simplify the responsibilities of the DSO considerably and leave the detailed capacity allocation to the entities directly in control of EV charging i.e. the FOs. There are also advantages to the FO since it will see a guaranteed capacity, free from stochasticity, early in the planning stage. Early information is valuable to an FO attempting to optimize charging to meet a variety of goals such as market services and individual driving needs.

Risk: There is the risk that a single kW limit set-point per grid node is too crude a mechanism to handle thermal loading - any unexpected change in base load during operation may void the DSO’s estimation of capacity shares which has been handed out to the FOs during scheduling. The risk in this approach also lies in the effectiveness and reliability of the FO bilateral capacity trading. If the FOs can not be trusted to handle the management and trading of capacity among themselves, there will be the need of a more formal framework, e.g. a market, and new definitions of responsibilities, such as the balance responsible parties seen in the energy market.

C. Dynamic Grid Tariff

In this solution, the distribution system operator generates a time and grid-location dependent price for grid usage based on expected nodal consumption levels. The DSO anticipates the size and the price-responsiveness of the load at critical grid nodes and calculates the price to
optimally reflect the expected congestion problem. FOs will then see a dynamic nodal tariff and can make an optimal schedule with respect to the e.g. spot price and dynamic grid tariff.

The method considered here has been presented in [23].

1) Operation sequence: The key operation aspects for this coordination strategy are outlined in Figure 5.

- In the planning stage, a distribution system operator would create models for the price-sensitivity of relevant demand clusters. These models would be updated on a regular basis based on learning from smart meter feedback.
- In the scheduling stage the forecasted demand, grid situation and present spot market prices will be employed to calculate appropriate branch prices for distribution grid utilization.
- The dynamic tariff is published to subscribers. The adapted branch prices are received by the fleet operator and employed to compute an optimal charging plan.
- During the operation stage, the charging schedule is executed. In case of severe underestimation or fluctuations of the actual demand, DSO controlled interruptions may occur in real-time.
- For settlement the timed consumption data is collected by the responsible DSO and the published prices will then be employed to bill the actual grid usage individually.

2) Evaluation: Complexity: The main characteristic feature of this approach is the simplicity of the interactions and also the simplicity of integrating simple prices in distribution grids.

The implementation complexity is high on the side of the DSO. This scheme cannot be established safely without interruptability of the vehicle charging.

For the Fleet Operator–Consumer interaction, the establishment of a satisfactory service quality may require more conservative estimates of the available capacity. Even though the increase of the utilization factor is therefore highly uncertain, the simplicity of the approach could justify its implementation.

For fleet operators and consumers, the benefits are also indirectly associated with the increased grid utilization. A further benefit can be seen in the flexibility this approach offers with respect to integrating other flexible demand units, as the price, in theory, could interpreted by any unit.

Risk: It is unclear whether a meaningful price-sensitivity of demand can be established.

There is a risk that there is no ‘right’ price to avoid overloading, if a sufficient number of EVs is connected to the same feeder, there is no way for them to negotiate capacity utilization in the given framework. Due to the required interruptability, the high chance for unplanned charging interruptions also implies an additional risk is on the side of the Fleet Operator / EV Owner.

V. DISCUSSION AND CONCLUSION

This paper has investigated the concept of congestion management for distribution grids, detailing the operations and interactions of two main stakeholders in three different coordination strategies. The purpose of the analysis was to highlight the cross-actor dependencies that each such strategy entails along the operation timeline, and thus to globally assess complexity, value and risk for each strategy.

Table I summarizes these evaluation parameters across the strategies and stakeholders. In this table the customer is represented by the FO.

The ‘distribution grid capacity market’ is expected to offer high value and low risk for both FO and DSO assuming a formalized, optimal and secure framework supplied by a well-designed market. such a market, however, may represent the most complex strategy to implement, which may hinder or delay its real-life implementation.

‘Advance grid capacity’ is relatively easy to implement, but would require over-the-counter trading to efficiently use available grid capacity. The strategy removes complexity from the DSO but some risk may have to be managed due to the bilateral FO trading and the advance capacity allocation might require more conservative estimates of the available capacity. The FO gains high value from early information on capacity availability.

‘Dynamic tariffs’ would also be easier to implement than a capacity market, but may prove challenging to the fleet operator due to added uncertainty and a possible conflict with system-wide smart charging schemes. It could also impose some extra risk for the DSO to rely on prices rather than hard capacity limits when considering individual feeder lines.
A few general observations can be summarized as:

- Grid considerations will have to co-exist with other objectives in the charging management of EVs.
- Coordination and information exchange in earlier stages can reduce complexity and benefit both the FO and DSO.
- There may be a trade-off between ease of strategy implementation and optimality. A compromise may be necessary for the first real-life implementations.
- A suitable strategy for coordination between DSOs and FOs will improve each stakeholders ability to reach its objectives considerably.

The analysis framework developed in this paper can be considered sufficiently generic for analysing operations with respect to other distributed resources.

An important mechanism included in this paper is the ‘real-time intervention’ functionality used by the DSO. This last-resort ability to directly and immediately reduce or disconnect charging may be a prerequisite for the deployment of effective coordination strategies.

In the end, it is hoped that this paper contributes to a better understanding of the multifaceted challenge of EV charging and helps the development of open, robust, and meaningful strategies for low voltage grid congestion management.

VI. References


VII. Biographies

Peter Bach Andersen has a M.Sc. in Informatics and is currently finalizing a PhD at the Department of Electrical Engineering within the Technical University of Denmark (DTU). His research focus is on smart grids in general but with a special emphasis on electric vehicle integration. Peter is an IEEE student member.

Junjie Hu received the Master of Engineering in Control Theory and Control Engineering from Tongji University, Shanghai, China, in 2010. Currently, he is a PhD student at the Department of Electrical Engineering within the Technical University of Denmark (DTU). His research focuses on integrating control policies on controllable load, mainly electric vehicle, for active power distribution system, of which the control policies are direct control and indirect (price) control. Junjie is an IEEE student member.

Kai Heussen is assistant professor at the Technical University of Denmark, where he also obtained his PhD on Control Architecture Modeling for Future Power Systems. He received his Dipl.Ing. in Engineering Cybernetics in 2007 from University of Stuttgart. His current research focus is the design of heterarchical and service-oriented control architectures for distributed control of power systems, with special attention to functional modeling and decision support for automation design.
B  A Comparison of Electric Vehicle Integration Projects

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Abstract -- It is widely agreed that an intelligent integration of electric vehicles can yield benefits for electric vehicle owner, power grid, and the society as a whole. Numerous electric vehicle utilization concepts have been investigated ranging from the simple e.g. delayed charging to the more advanced e.g. utilization of electric vehicles for ancillary services. To arrive at standardized solutions, it is helpful to analyze the market integration and utilization concepts, architectures and technologies used in a set of state-of-the art electric vehicle demonstration projects. The goal of this paper is to highlight different approaches to electric vehicle integration in three such projects and describe the underlying technical components which should be harmonized to support interoperability and a broad set of utilization concepts. The projects investigated are the American University of Delaware’s V2G research, the German e-mobility Berlin project and the Danish EDISON project.

Index Terms -- Electric Vehicles, Distributed Energy Resources, Smart Grid, Standardization, Information and Communications Technology.

I. INTRODUCTION

Common to most electric vehicle (EV) power system integration projects are that they aim to prove that the EV, when seen as a distributed energy resource, can offer value and services that exceeds its primary function as a means of transportation. The value and services investigated can, for instance, be the minimization of charging costs, adherence to grid constraints or adjustment of charging behaviour to renewable energy production [1]-[3]. In practise, however, projects often differ in how the above is actually achieved.

A standardized approach to electric vehicle integration has many benefits including the support of roaming and a consistent support of advanced grid related services.

A good input for standardization is the research and demonstrations already done in the area of EV integration. For three such projects we use a set of parameters to categorize and compare the approaches and components used in each.

The parameters used in this paper are:

- **Market integration and EV utilization concept**
- **Architecture**
- **Technology and standards**

By 'market integration' is meant the way that the EV, directly or indirectly, is connected to the power market to generate savings and possibly revenue for the EV owner. The number and composition of market stakeholders involved depends heavily on the business models and market environments under consideration. Market integration approaches could both be aimed at current energy and power markets or future, more dynamic, near real-time markets using price signals. The latter is researched in the ECOGRID.EU project [4].

Related to market integration is the 'utilization concept' in question. 'Utilization concept' covers which functionalities the EV will support and can roughly be categorized into the two following categories:

- **Smart charging** - Where the charging of an EV battery is delayed or advanced in time based on energy costs, grid constraints or renewable contents. Essentially the EV is used as a controllable load.

- **Energy backup and power services** - The Vehicle-to-Grid (V2G) concept, where power is delivered back to the grid from the EV battery, belongs in this category. V2G can increase the EV’s ability to provide regulating services.

The market integration and utilization concept chosen shapes the architecture of a project. By 'architecture' is meant the stakeholders and mechanisms used to influence the EV’s behaviour and interface it with the power system and market.

Three different 'generic' architectures are proposed by You Shi et. al. [5] for the concept of Virtual Power Plants, which also represents the architectural options in EV integration.

- **Centralized control** - In which a single entity (an aggregator) directly controls the behaviour of a group of electric vehicles.

- **Partly centralized** - In which a negotiation is taking place between the individual EV and the aggregator. The aggregator would thus only indirectly influence the behaviour of the EV.

- **Fully distributed** - In which the EV behaves as an autonomous and intelligent agent that could interface directly with the power grid and/or the market.

The fully distributed architecture is strongly related to the market integration concept and can be expected to be used in more centralized architectures.

The final parameter used for the comparison is 'technologies
and standards'. The technology descriptions of the projects cover two topics. First, the components in both soft- and hardware which has been developed to support the computation and logic necessary for managing smart or bi-directional charging are mentioned. Secondly, the communication protocols used for transferring data between the entities are listed.

Related to technologies are the standards used by the projects. The standards can be subdivided into those dealing with communication and information models and those that deal with equipment and hardware.

The remainder of the paper is organised as follows. The following, 'EV integration projects' section will describe the EV integration approach used in three different EV integration projects by using the parameters defined above. Next, the 'Project comparisons and recommendations' section will highlight the similarities and difference between them and then explore the potential of standardization. Finally, the paper will summarize its findings and suggest future focus areas in the 'Conclusion' section.

II. EV INTEGRATION PROJECTS

This section will introduce two European and one American EV integration project. They have been chosen since they represent some of the biggest and most innovative research projects within the field. These are however far from the only ones and projects such as MERGE [6] (Mobile Energy in grids of electricity) could also have been included. Such projects represent mature investigations where a lot of experience have already been accumulated. The experience gathered is, apart from an input to standardization, also a good point of departure for a new generation of EV projects.

Among the absolutely largest among the newest generation of projects are the European ‘Green eMotion’ project [7] with more than 40 partners and a 42 Mio. EUR budget. In the states the huge ‘The EV Project’ [8] represents the largest EV charging infrastructure project to date counting more than 60 participants and including thousands of EVs.

The three projects specifically chosen in this paper all share certain traits when it comes to the integration approach followed. They are all 'economic' integrations where money is earned through market participation. They also share a focus on existing markets and implement an either centralized or partly centralized architecture. Such similarities could be seen as a prerequisite for arriving at common solutions applicable for all such projects. There are, however, still many differences in the implementations which illustrates the challenges to standardization.

This paper focuses on four main entities which are present in all three project; The EV, the EV User, the Electric Vehicle Supply Equipment (EVSE) and the more generic Aggregator role, which would represent the 'interface' between a group of EVs and the power system or energy market.

As will be shown by the following, the projects differ in by which means the above entities should communicate, what information should flow between them and, in the end, which entity will control the behaviour of the EV.

A. The Edison project

EDISON [9]-[10] is short for 'Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks' and is a research project partly funded through the Danish Transmission System Operator (TSO) - Energinet.dk.

The goal is to develop optimal solutions for EV integration, including network issues, market solutions, and optimal interaction between different energy technologies. The technical platforms developed by EDISON should be globally applicable and is tested on the Danish island of Bornholm.

The EDISON consortium consists of the Danish utilities DONG Energy and Østkraft, the Danish Technical University (DTU), as well as IBM, Siemens, Eurisco and the Danish Energy Association. The three year project will conclude in 2012 but might be followed by an EDISON 2 project. The project webpage can be found at www.edison-net.dk.

1) Market integration and EV utilization concept

While several market integration concepts are within the research scope of EDISON, the initial focus is on the current Nordic NordPool market. Within NordPool the EVs can either be connected to the day-ahead energy market, be used for intraday regulation or for reserves. The first project phase puts its emphasis on the first and indirectly connect the EVs with the day-ahead spot market by controlling the charging in correspondence with hourly energy prices. This follows the smart charging utilization concept.

2) Architecture

The setup shown in figure 1 represents the implementation done in EDISON. The setup uses a centralized architecture where an aggregator, called the 'fleet operator' in EDISON, directly controls the charging patterns of the EV to facilitate smart charging. The conceptual role of a fleet operator could be maintained by any commercial party willing to adhere to the requirements of the Nordic power market. An EV in EDISON is seen as relatively simple with little local
intelligence. The argument is that most OEM EVs initially will lack the capabilities for local optimization. The EV needs only to implement an interface that would allow the fleet operator to extract status information, such as state-of-charge, and possible constrains set by the OEM. In Edison the charging spot would play the role of a ‘proxy’ in that it would extract EV information and manage smart charging on behalf of the fleet operator. The user will in EDISON communicate her or his charging preferences directly to the aggregator.

3) Technologies and standards

Between EV and EVSE, EDISON utilizes the IEC 61851 standard which describes the charging of EVs using different AC or DC power voltages over a conductor using on- or off-board equipment. Apart from specifications for equipment interoperability and safety, the standard also defines simple EV-EVSE communication via a control pilot wire using a pulse width modulated (PWM) signal with a variable voltage level. This allows the EV to communicate its state to the EVSE. IEC 61851 is used in EDISON since it helps satisfy safety requirements and will improve interoperability.

The IEC 62196-2 Type 2 Mennekes plugs are used on the conductor connecting EV and EVSE.

Apart from the control pilot wire, EDISON uses Power Line Carrier (PLC) communication to support the exchange of information. Although not part of IEC 61851, this technology is a valid candidate for future standardization.

An EDISON I/O board is installed at the EV and the EVSE and includes a PLC adapter.

To connect the EVSE with the aggregator, the IEC 61850 standard is used. IEC 61850 was originally aimed at substation automation, but has been expanded to cover the monitoring and control of distributed energy resources. The standard includes a reusable data model which can be used to monitor and control both the EVSE and the EV.

The EVSE implements an IEC 61850 compliant server which uses HTTP/HTTPS based RESTful web services, instead of the MMS protocol traditionally associated with IEC 61850. The REST interface is combined with the SIP application level protocol to better facilitate scalability. The use of Transport Level Security (TLS) is used to provide data confidentiality.

After the aggregator has extracted information through the REST interface of the IEC server it uses a software platform called the EVPP (EDISON Virtual Power Plant) that, through prediction and optimization, will compute a suitable charging strategy. The strategy is described using an IEC 61850-7-420 Energy and/or Ancillary Services Schedule (DSCH) which is sent to the EVSE IEC server. The schedule consists of a set of power set points and timestamps which will be followed by the EVSE during the charging of the EV.

An iPhone App and a webpage have been developed for the user to define charging requirements.

B. Vehicle to Grid technology, University of Delaware

Vehicle-to-Grid (V2G) technology [11]-[12] is researched and developed at the at the University of Delaware (UD). The research focuses on the potential that V2G technology has for improving the utilization of the EVs as active resources in the grid and market. The research done by UD V2G spans a broad set of disciplines such as soft- and hardware development, grid impact and driving pattern analysis and aggregated fleet optimization. In addition to the technical aspects, UD V2G also covers policies, standards, legislation and user adoption. For testing and demonstrating, UD V2G uses a fleet of V2G enabled vehicles.

UD V2G is both a project and a research program and will continuously work within research, development and commercialization of V2G. Recently the group has started replacing the term ‘V2G’ with ‘Grid Integrated Vehicle’ to emphasize the importance of grid integration.

AC Propulsion, a manufacturer of battery and propulsion systems, is an active partner in the project. The research is supported by the US Department Of Energy (DOE) as well as several American utility companies.

More information is available at www.udel.edu/V2G.

1) Market integration and EV utilization concept

The UD V2G market integration concept has been tested by participating in the regulation services market where the vehicle responds to regulation power requests sent from an Transmission System Operator (TSO). The Bi-directional charging utilization concept will allow the EVs to react to TSO requests for both up and down regulation and the EV User will be economically compensated for such services [13]. Regulating services has been implemented by UD V2G since it represents one of the most profitable markets to participate in. UD V2G publications have noted that their control mechanisms are also designed for other TSO markets such as spinning reserves, and for distribution system services such as peak load reduction, valley filling, reactive power, and transformer upgrade deferral, but UD V2G cars are not actually participating in these markets yet.

2) Architecture

The UD V2G architecture depicted in Fig. 2 can be classified as partly distributed since the EV implements an intelligent agent that will use a negotiation-like communication towards the aggregator. The EV will control the charging...
process and be responsible for predicting and satisfying the energy requirements of the EV user.

Adding local intelligence and control in the EV can supply a better separation of concerns where a 3rd party, like the aggregator, would not have full control over charging and free access to utilization data. This secures the EV against external mismanagement (e.g., driver’s need for driving range has priority) and simplifies the optimization in the aggregator.

The purpose of the EVSE in the UD V2G architecture, aside from facilitating the power supply and internet connection, is to supply information on possible grid-related charging constraints. The user can through a web interface formulate her or his driving requirements. The collected trip information is then feed to the vehicle.

3) Technologies and standards

In the UD V2G project setup, an electric vehicle contains a Vehicle Smart Link (VSL) implemented on a automotive-grade Linux computer. The VSL will communicate with the Vehicle Management System (VMS) and Battery Managements System (BMS) of the EV to get battery information and to control charging. The Society of Automotive Engineers (SAE) J1772 standard is used for the equipment connecting EV and EVSE. J1772 defines the electrical and physical characteristics of conductive charging equipment connecting EV and EVSE.

The architecture of e-mobility Berlin

1) Market integration and EV utilization concept

The aggregator in the e-mobility project is initially seen as the utility company e.g., RWE, who could sell energy to EV users and reward them for flexibility. By letting the user specify an ‘end of charge’ time the utilization concept of smart charging is supported. E-mobility does not directly address bi-directional charging and the use of the EV for ancillary services.

2) Architecture

The e-mobility project puts a lot of emphasis on the EV-EVSE interaction in its architecture. As illustrated in Fig. 3 the EV acts as a client towards a server implemented at the EVSE. The tariffs and charging options of the utility company will be represented by the EVSE which will serve as a proxy.

Despite the presence of an aggregating entity, the setup is open for additional unspecified utilization concepts.

3) Technologies and standards

Each car is equipped with a Smart Charge communication unit which can communicate with the EVSE by using the e-mobility Smart Charge Protocol (SCP) over PLC. The SCP
defines a series of application level messages which are sent back and forth in the following sequence. After a plug-in has been detected, 'identification' messages will be used to configure the connection session and to establish identification, billing and contract details (for roaming). The EV will then request a list of EVSE provided services in a 'service discovery' message. Services include the charging and payment options available at the specific EVSE. The EV will then send its energy demand and intended charging behaviour in a 'power discovery' message. The EVSE will compare the charging behaviour with knowledge on local grid and equipment capabilities and send back price listings. When charging and billing has been settled, a series of messages initiates the power connection and monitors the charging process. SPC messages are encoded according to the Smart Message Language (SML) which is a mark-up language similar to XML that has been used for smart meter communication. Transport Layer Security (TLS) is used to supply data confidentiality through encryption. The DoIP protocol is used for EV diagnostics.

The e-mobility project has contributed significantly to the standardization of the IEC IEC 62196-2 Type 2 compatible Mennekes plug. The EVSE equipment supports conductive charging in accordance to IEC 61851.

III. PROJECT COMPARISONS AND RECOMMENDATIONS

The investigation of the three EV integration projects has revealed a series of differences and similarities which can be used to identify the areas that should be addressed by standardization. Fig. 4 compares the three projects based on the parameters described in the previous sections.

A. Comparison - Market integration and EV utilization concept

Markets integration concepts for EVs will most likely vary based on local market conditions and are, for the centralized architectures, tightly linked to the business cases chosen by the aggregator. Smart charging, as covered by EDISON and e-mobility, can be seen as a first approach to market integration by allowing the EV to respond to variable energy prices on the energy market. The V2G equipment tested by UD V2G can be seen as the second step where the EV increases its potential as a resource to the grid and more market integration concepts becomes possible. New integration concepts might occur over the coming years as markets will adjust to better handle distributed energy resources as part of the smart grid concept. By letting standards support as many utilization concepts as possible, it is ensured that a broad set of integration concepts will be possible in both present and future markets.

B. Comparison - Architecture

The differences in the architectures of the three projects are an indication of a fundamental question in EV integration: Which entity is responsible for influencing or controlling the EVs utilization behaviour? Is it the aggregator, the EVSE or the EV itself?

Both e-mobility and UD V2G uses an EV-centric approach where an embedded computer in the vehicle will take certain decisions. Both the centralized and distributed architecture comes with a set of advantages. Theoretically, however, whether the controlling logic is placed at the aggregator or in the individual EV should not matter as long as optimization objectives are the same and EV User SLA’s are strictly followed. One solution could be to have the infrastructure support a set of standardized architectures so that, for instance, both 'self managing' and 'non self managing' EVs can charge using the same equipment.

C. Comparison - Technologies and standards

As can be seen on figure 4, EDISON is the only project to use a standardised communication approach between EV and aggregator, namely IEC 61850. There are advantages to using an approach as well-described and widely applied as IEC 61850 and initial tests by EDISON indicates that the standard either supports, or can be extended to support, the utilization concepts described in this paper.

A possible drawback of IEC 61850 is that it offers a structural decomposition of equipment as it is typically seen in SCADA applications. Technical de-composition means that the data model of IEC 61850 is designed to precisely represent physical components (inverters, chargers, relays etc.) and their operational status values. This can be argued to only make sense in a fully centralized architecture where direct and detailed access to equipment is appropriate. New standards will appear that ultimately might replace IEC 61850. Both e-mobility and EDISON have partners involved in the standardization around 'ISO/IEC 15118 – Vehicle to grid communication interface' which could have a major influence on future EV communication. On the SAE side J2836, J2847 and J2931 are addressing similar issues.

Standards that describe the equipment used for conductive charging are used in all three projects. The IEC 61851 and IEC 62196-2 standards used in the European projects are similar to SAE standards used in the American UD V2G project. Adoption of these standards bodes well for roaming support. Especially Daimler in the e-mobility project is deeply involved in both IEC, ISO and SAE standardization work.
These efforts could help bridge the gap between European and American EV standards.

The projects all use the internet and the associated IP stack in the communication solution as well as PLC on the physical level. The UD V2G group claims that wired communication is required to precisely identify the EVs location on the grid. Wireless communication, however, might become standard in EVs as new features and services become popular and it is claimed that 4G will have a major role in smart grids in general. If the localisation issues mentioned by UD V2G can be overcome, Wireless technologies should be considered a potential candidate for future EV communication standardization.

While the projects are aligned on the lower parts of the OSI stack, they are very divided on the application level protocols. The solutions span from the structural decomposition used by IEC 61850 to the use of agent software. Application level protocols for EV communication must be aligned, or at least compatible, to support roaming above the equipment level.

All projects use the transport level security (TLS) cryptographic protocol as part of the communication stack. This is a well tested protocol used, for instance, in internet banking. This protocol alone, however, does not address all cyber security issues that the ICT architecture will face. It is recommended to align EV communication security with smart grid related security standardization work of IEC TC57 WG 15 (e.g. IEC 62351) and NIST (e.g. 'Smart Grid Cyber Security guidelines')[15].

IV. CONCLUSION

The following are the key findings and recommendations by this paper based on the project comparison:

• **Market integration** - Present and future market integration concepts will improve the utilization of EVs as active resources in the power market and system. Market integration concepts could take many forms and should ultimately be left to the businesses driving the aggregators. Equipment and communication standards should support as many utilization concepts as possible, so that the EV may be used in as broad a range of market integration concepts.

• **Architecture** - The placement of control logic and responsibilities between EV, EVSE and aggregator, differs between the integration projects investigated. One key question is how much intelligence will be implemented at the EV. If a common architecture is not found, then standardization efforts must respect and manage the resulting diversity.

• **Communication standards** - A new class of standards covering EV communication, such as ISO/IEC 15118, are emerging. These standards should ideally support a broad set of utilization concepts. If, however, vehicles and EVSEs will be built to support very different architectures, one common solution is less feasible.

• **Equipment standards** - The Projects in question aligns nicely with the European and American standardization work - This trend brings great promise for roaming on the equipment level.

• **Communication protocols** - While the use of the internet protocol stack on top of PLC is used in all projects, application layer protocols differs significantly. These protocols should be aligned, or at least be compatible. Wireless communication for EVs is not used in any of the projects but could be considered a valid candidate for future work.

• **Security** - Transport level security, as used by all three projects, does not address all security concerns, but is a well-tested internet protocol suitable for handling confidentiality. Standardization aimed at smart grid security in general is also applicable for EV integration. Existing standards and guidelines by IEC and NIST should be considered.

If the above recommendations are considered, it will help promote a standardized platform for EV interoperability and grid integration. Such a platform can help realise two different potentials. The first is roaming that can help better servicing of driving requirements of EV owners and improve the utilization of infrastructure. Another potential is that most home charging equipment and EVs, across a series of different OEMs, will support smart grid integration and smart charging. Realising both of the above potentials will substantially aid and promote the cause of electric transportation.

V. REFERENCES


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VI. BIOGRAPHIES

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C Smartly Charging the Electric Vehicle Fleet

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SMARTLY CHARGING THE ELECTRIC VEHICLE FLEET

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15.1 INTRODUCTION

The Danish EDISON project [1–3] has been launched to demonstrate how the charging and possible discharging of electric vehicles (EVs), if handled intelligently, can yield benefits to the EV owner, the grid, and society. EDISON is partly publically funded through the Danish transmission system operator (TSO) Energinet.dk’s research program FORSKEL. The total budget is approximately EUR 6.5 million, with EUR 4.5 million thereof coming from FORSKEL. The consortium consists of the Danish energy corporations DONG Energy and Ørsted, the Danish Technical University (DTU) CETO and Risø, as well as IBM, Siemens, EURISCO, and the Danish Energy Association (DEA).

While the more progressive concepts such as using the EVs as energy storage or for regulating services using V2G show great promise, the EVs potential as a controllable load could be seen as the low-hanging fruit in EV integration. The smart
charging concept, where the charging of EV batteries is delayed or advanced in time based on energy costs, grid constraints, or renewable contents, has great potential and is the initial focus of EDISON. The success of smart charging, however, relies on a suitable and standardized ICT architecture. This chapter documents the suite of contemporary communication technologies, components, and standards, which helps to facilitate smart charging in the EDISON project. The chapter is organized as follows. First, Section 15.2 describes the integration scenario used in the EDISON project and introduces the fleet operator as a new stakeholder in the power system. The objectives of the fleet operator will be described along with the requirements of the ICT architecture that supports its operation. Next, Sections 15.3 to 15.5 describe the standards and standardization work relevant to the project, a set of EDISON-developed hardware and software components and the communication technologies used to interface the main entities.

The final parts of the chapter, Sections 15.6 and 15.7, present a set of demonstration interfaces and draw conclusions on the utilization of communication technologies in EDISON.

15.2 THE FLEET OPERATOR AS A NEW CONCEPTUAL ROLE

The conceptual role of a fleet operator, which can be taken by different commercial players, is introduced to allow groups of EVs to be actively integrated in the power system. Toward the grid and market stakeholders, the fleet operator will operate as a virtual power plant (VPP). The virtual power plant concept describes an aggregated system in which distributed energy resources (DERs) are partly or fully controlled by a single coordinating entity. In this way, DERs can be actively integrated into the power system and market, for which individually they would be too small, in terms of power output and availability, to participate in. The concept has been demonstrated in the European FENIX project [4] and studied by Shi You et al. [5].

In the case of EDISON a fleet operator could mimic a traditional power plant by aggregating a group of electric vehicles. The fleet operator would also need to interact with each individual electric vehicle to optimize charging. The technical implementation of this concept is called the EDISON VPP (EVPP) and would be used by a fleet operator as shown in Figure 15.1.

15.2.1 Fleet Operator Interaction with Grid and Market Stakeholders

A first step in EV integration is identifying the stakeholders, old and new, that will have a role to play in interfacing the EVs with the power system and market. The composition of stakeholders depends heavily on the business models and market environments under consideration.
The EDISON fleet operator integration scenario is based on the current Nordic power system and market configuration. There are obviously many other integration concepts such as near real-time markets, frequency response, or price signals in which the vehicle acts as an autonomous and intelligent agent. While such concepts are within the research scope of EDISON, the phase-1 scenario will focus on conditions as they are today and is a pragmatic first approach to EV integration. Figure 15.2 shows the market domain model in which the fleet operator interfaces the EV with the power market. Among the stakeholders in this domain is the transmission system operator (TSO), which controls the transmission grid and maintains the overall security of electricity supply, and the distribution system operator (DSO), which manages a part of the distribution grid and handles local metering. The fleet operator must maintain the appropriate balancing responsibilities when acting on the markets.

As illustrated, the fleet operator could participate either in the energy market or in ancillary services. The first project phase, however, will put its emphasis on the former and indirectly connect the EVs with the day-ahead spot market by controlling the charging in correspondence with hourly energy prices.
15.2.2 The Objective of the Fleet Operator

Based on the market integration and stakeholder setup, as described above, the primary objective of the EVPP fleet operator is to facilitate smart charging. Under smart charging, we understand the computation of a per EV charging schedule, which is computed using some predetermined optimization targets as well as a set of constraints. The objectives of the charging schedules are primarily to ensure that sufficient energy will be delivered to the EVs such that future trips can be carried out. Sufficient energy can be further refined into energy objectives, that is, an 80% full battery or a more precise, per-trip, energy objective.

Aside from the primary objective of supplying energy for the use of driving, other objectives can be defined:

- **Minimizing Energy Costs.** Charge at the time periods with the lowest energy prices.
- **Respect Grid Constraints.** Adjust charging to capacity limitations of the distribution grid.
- **Renewable Content.** Charge during periods when underutilized renewable energy is produced.

This results in a multiobjective optimization problem where a solution requires that a compromise between the objectives is found. For example, optimal use of renewable energy will not guarantee a minimization of charging costs. This optimization is done in the EVPP software, which is described in Section 15.4. The mathematical techniques used by the EVPP are addressed by Olle Sundström and Carl Binding in the paper “Optimization Methods to Plan the Charging of Electric Vehicle Fleets” [6], where linear and quadratic optimization methods are investigated for charging schedule generation. The paper “Planning Electric-Drive Vehicle Charging Under Constrained Grid Conditions” [7], by the same authors, add distribution grid considerations to the optimization.
15.2.3 ICT Architecture Setup and Requirements

A fleet operator will require a suitable ICT architecture that can connect the stakeholders and let them exchange the information necessary for smart charging. The ICT architecture in EDISON is based on the setup shown in Figure 15.3.

The figure shows the four entities directly involved in electric vehicle (EV) smart charging. In this setup the electric vehicle supply equipment (EVSE) facilitates the connection between EV and fleet operator. The EVSE will extract information from the EV and share it with the fleet operator. The EVSE will then receive a charging schedule from the fleet operator and follow it in the charging of the EV. Since the charging decisions are delegated to the fleet operator and communication is handled by the EVSE, this setup will support most "simple" EVs with limited computation and communication capabilities. As future EVs evolve into more autonomous and intelligent agents, the setup will most likely change. Based on the above setup the following requirements of an ICT architecture have been defined.

- **Adherence to Standards.** EDISON attempts to identify, and to some extent implement, the standards most relevant to its architecture. The chosen standards are IEC 61850 and IEC 61851 as well as the coming ISO/IEC 13478, which will be described in Section 15.3.

- **Implementation of Smart Charging Components.** EDISON must develop a set of hardware and software components that support smart charging for demonstration purposes. This includes software running on the EVSE and fleet operator platforms and the I/O components necessary to connect the EV to the EVSE. These components are described in Section 15.4.
• Interfaces that Satisfy Basic Communication Requirements. The protocols connecting the main entities in the EDISON setup must satisfy such requirements as interoperability, scalability, and security. Since the EVSE acts as a proxy for the EV toward the fleet operator, the main focus is on the communication between EVSE and fleet operator. The communication protocols and techniques chosen for the architecture will be described in Section 15.5 along with arguments for including them. See Chapter 10 for an overview of Smart Grid protocols.

The rest of the chapter will attempt to describe how the above requirements have been met.

15.3 EDISON AND THE USE OF STANDARDS

The EDISON project should produce technical components that are reusable and applicable across different projects and geographies. This requires that the components, as far as possible, conform to a set of standards. By using and supporting standards, the project may also offer input and recommendations for the continued standardization process.

This section describes contemporary standards on which the EDISON ICT architecture is based. As seen in Figure 15.4, these standards can be split into two groups: the ones used for performing (1) EV-to-EVSE and (2) EVSE-to-fleet operator communication, respectively.

IEC 61850 is the communication standard used by EDISON. This standard is not specific to EVs, but supplies the necessary components to describe and send relevant data between EVSE and fleet operator. The IEC 61851 focuses on the

![Figure 15.4: Standards used in EDISON.](Image)
physical connection and charging of an EV. The future ISO/IEC 15118 deals both with the physical interconnection and a high level communication protocol that, as opposed to IEC 61850, will be oriented toward data and services specific to EVs. Although the ISO/IEC 15118 standard will not be ready for implementation by EDISON, its relevance to EV integration justifies a brief mentioning in this section.

15.3.1 Standards Between Electric Vehicle and Electric Vehicle Supply Equipment: IEC 61851 And ISO/IEC 15118

Between the EV and the EVSE, the following two standards with special relevance to EDISON have been identified.

15.3.1.1 IEC 61851. The “IEC 61851—Electric Vehicle Conductive Charging System” standard was first published in 2001 and has been released in a 2nd edition in 2010. It describes the charging of EVs using different AC or DC voltages over a conductor using on- or off-board equipment.

The main topics of the standard are:

- General system requirements and interfaces
- Protection against electric shock
- Connection between the power supply and the EV
- Specific requirements for vehicle inlet, connector plug, and socket outlet
- Charging cable assembly requirements
- EVSE requirements

“General System Requirements and Interfaces” covers the definition of four different charging modes that an EVSE can support. These modes vary in the currents they support, safety requirements, and location of the charger (in the EV or in the EVSE). EDISON must, for instance, support mode 2 to allow for up to 32 amperes with three phases charging using an onboard charger.

IEC 61851-1 supports the plugs defined by IEC 62196-2. IEC 62196-2 specifies the requirements for plugs, socket outlets, connectors, inlets, and cable assemblies. Among the plugs to adhere to IEC 62196-2 is the Mennekes EV plug, which was developed and tested during the German e-mobility projects and is close to becoming a common European standard.

Another important component of the standard is the definition of simple EV–EVSE communication via a control pilot wire using a pulse width modulated (PWM) signal with a variable voltage level. This allows for the definition of different “states,” which are listed in Section 15.5 within the description of the EV–EVSE interface.

The use of IEC 61851 is relevant to EDISON for several reasons. First, the safety recommendations described by the standard could be essential in having the developed components approved for live demonstrations. Second, adherence to standards...
such as IEC 61851 is one of the prerequisites for roaming, allowing EVs of various brands to use EVSE from different manufacturers.

15.3.1.2 **IEC/ISO 15118.** The standardization process involving “IEC/ISO 15118—Vehicle to Grid Communication Interface” is still ongoing. The purpose is to make a standard for scenarios that require advanced communication between EV and EVSE.

The standard is divided into the following three parts:

1. IEC/ISO 15118-1 (General Information and Use Case Definition)
2. IEC/ISO 15118-2 (Message and Protocol)
3. IEC/ISO 15118-3 (Physical Layer)

The first part (15118-1), which describes the use cases and terms and definitions, is currently in a Committee Draft (CD) stage and the following use case elements have been identified (Figure 15.5).

In the EDISON project IP-based communication will be implemented, including the use case elements above. The “Value added services” element could include smart charging as defined by EDISON. Adherence to IEC/ISO 15118 would further benefit roaming.

15.3.2 **Standard Between Electric Vehicle Supply Equipment and Fleet Operator: IEC 61850**

For a couple of decades, the IEC 61850 standard has been one of the preferred ways to relay information and control within the domain of substation automation. Lately, though, with the added support for distributed energy resources in the form of the
IEC 61850-7-420 substandard, it has moved out of the substation domain to see much wider use.

As illustrated in Figure 15.6 the IEC 61850 standard is highly modular and consists of a large collection of hierarchical building blocks, with which almost every feasible piece of electrical equipment can be modeled. Starting from the top, the device is represented by a logical device. This in turn consists of a series of logical nodes representing various components within this device, and for every layer the granularity becomes even finer. This continues toward the bottom of the structure, where basic data types like strings, Booleans, and integers or floating point numbers make up the final link.

The structure illustrated in Figure 15.6 shows a part of a charging spot model, specifically the total consumption (TotW), which is a data class of type Measured Value (MV), is contained in an MMXU logical node. The latter is defined in the basic IEC61850 standard and is used to represent power system measurements. Because TotW is an MV class it contains the data attribute for magnitude (mag), which in turn contains the floating point value in question.

15.3.2.1 IEC 61850 with -7-420 Extension. To move the use of the IEC 61850 standard beyond that of the substation environment for which it was designed, an extension called IEC 61850-7-420 was developed to add the necessary logical nodes needed for communicating with distributed energy resources (DERs). Wherever possible, the extension makes use of the existing logical nodes; the standard defines nodes for generation and storage devices, including reciprocating engines, fuel cells, microturbines, photovoltaic arrays, combined heat and power units, and batteries. While IEC 61850-7-420 has been released as an international standard, development of the extension is an ongoing process and logical nodes are being redefined as well as added. During the course of the EDISON project, a proposal was made to extend the standard with logical nodes for both a charging spot (DCHS) and an electric vehicle (DBEV).

15.3.2.2 IEC 61850 Energy and Power Schedules. Sometimes trying to enforce instant control over distributed energy resources (DERs) is not desired and

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Figure 15.6. The hierarchical structure of an IEC 61850 model.
for this reason the IEC 61850-7-420 extends the standard with the logical nodes for handling absolute and relative timed energy schedules. Consisting primarily of a group of arrays, one of the logical nodes allows for the definition of a series of power setpoints and ramp types together with individual timestamps or time offsets. The usage can vary greatly, allowing the scheduled production of generators, the load of pumps, or, in the case of the EDISON project, the charging schedules for the electric vehicles. Figure 15.7 illustrates how such a charging schedule might look, defining the load the vehicle charger should draw from the grid at the various times specified in the schedule. Though not implemented as yet, support for vehicle-to-grid is easily done with the power schedules by simply stating negative power setpoints.

15.4 SMART CHARGING COMMUNICATION COMPONENTS

This section describes the software and hardware components that have been developed in EDISON to implement the communication interfaces and facilitate smart charging.

As illustrated in Figure 15.8, the components covered in this section will be the I/O board located in the EV and the EVSE, the IEC 61850 compatible server, and the EVPP software used by the fleet operator. The following sections will cover these components in turn.

15.4.1 The IEC 61850 Server

Early on, in the course of the work done in EDISON’s work package 3, the IEC 61850 standard was chosen as the main communication protocol between the EVPP and the EVSE.
In order to aid developing and testing, and to get rid of proprietary dependencies, an IEC 61850 enabled server was developed. To further facilitate the interoperability between parties within EDISON, the server was designed with a mapping of the standard to so-called *representational state transfer* (REST) web services. The use of REST services is described in greater detail in Section 15.5.2. Due to its modular construction of the IEC server, it can, however, be extended to support other protocols should the need arise. As seen in Figure 15.9, which gives an overview of the primary server components, the setup comprises three layers. In the middle is the server core, sandwiched between the communication layer and the device modules. The same modularity that enables additions of communication protocols also allows
the server to support any number of devices through the use of device-specific plugin modules. In the course of the EDISON project, modules have been written for anything from photovoltaics, wind turbines, micro combined heat and power units, and of course charging sports and electric vehicles.

Successful tests have been carried out with all of the above running off the same server instance. Because electric vehicles have not always been available when needed, and in the quantities needed, a simulation was developed as a specific plugin device module, enabling any client to access the simulated vehicles and charging spots through the IEC 61850 protocol—as if they were real.

15.4.2 The EDISON VPP

The EDISON VPP is a piece of server-side software that coordinates the behavior of a fleet of EVs while communicating with external power system stakeholders. To illustrate the internal workings of the EVPP, it can be useful to group its functions into three groups: data, analytics, and logic. This is done in Figure 15.10, which also differentiates between the aggregated and the individual level of EV management.

Basically, the EVPP handles the EV fleet as an aggregated group when acting and optimizing toward market players (upper interfaces), but will have to take individual considerations into account when handling the behavior of a single car (lower interfaces). The three main functional groups perform the following:

![Diagram of EVPP functionality](Figure 15.10. EVPP functionality.)
• **Data.** This group stores previous market prices and fleet behavior on an aggregated level, enabling better forecasting and optimization for acting on the power market. On an individual level, data are stored that describe the service level agreement between the EVPP and an EV owner, for example, to which degree the EVPP should control the charging process. EV hardware specifications, like battery size and supported charging powers, are also stored. Finally, the EVPP stores the EV users plug-in habits, that is, where, when, and for how long the EV is typically connected to the grid for charging. These parameters are all vital for individually optimizing the charging of an electric vehicle.

• **Analytics.** Analytics means the mathematical computations necessary to support the logic of the EVPP. Forecasting relies on historical data to predict market prices on an aggregated level, which supports better bids and strategies. Forecasting also determines future individual EV usage patterns. The latter helps the EVPP predict when the EV user will need the EV for the next trip and can thus better estimate the time period available for smart charging. Such a prediction can be based on the statistical methods of exponential smoothing or using the Markov chain approach.

Optimization is used to minimize charging costs of the EVs on both the aggregated and individual level. The individual optimization is limited by the constraints introduced by the distribution grid, EV specifications, and EV user energy requirements. On the aggregated level, profit maximization can be done when acting on the regulating and reserve markets. Such optimization can be achieved through stochastic or linear programming.

• **Logic.** The logic defines the main operational goals of the EVPP, namely, to act on the power market to generate savings or revenue for itself and its clients, and to intelligently manage the charging behavior of EVs through individually tailored charging schedules.

The operation of the EVPP is illustrated through the EVPP panel interface, which is described in Section 15.6.

### 15.4.3 The EDISON I/O Board

The EDISON I/O board was developed to allow testing of the interface described in the IEC 61851-1 standard, by handling the initial signaling between EV and EVSE. Furthermore, it facilitates the communication with the internals of both the EV and the EVSE and the exchange of information between EV and EVSE.

Figure 15.11 shows the conceptual overview of the features of the I/O board. The board itself has virtually no processing power and in common terms only provides a means of transportation (the envelope) without knowing what is being transported (the content). Hence, an external controller is needed to utilize the features of the board and handle the business logic in the application. As the features needed by an EV and an EVSE are slightly different, the board shall be configured to be used
### 15.5 Charging Infrastructure Communication

The main interfaces investigated are those between the EV, the EVSE, the fleet operator, and the EV User, all of which can be seen in Figure 15.12. The following will describe the main protocols and technologies used in the interfaces that connect the stakeholders.
15.5.1 Interface Connecting EV to EVSE

The question of how to connect the EV with the EVSE is both a question of which physical medium to choose and which standards and protocols to follow. The two main communication technologies that could be considered are wireless and wireline, as discussed in Chapters 6 and 7, respectively.

The use of wireless technologies is researched in several Smart Grid applications to allow for network communication. Wireless technologies such as GSM, GPRS, and 3G are well tested and are valid options for transferring data to and from EVs. The upcoming 4G technology will increase support for applications where high data rates are required. If, or when, all EVs require connectivity for features beyond managing the charging, a constant Internet connection supplied by, for example, 4G could become a necessity.

If, however, the EVs only need Internet connectivity for the purpose of smart charging, such a connection only needs to be maintained for the duration of the electrical connection. In other words, the fleet operator primarily needs to communicate with the vehicle when it is plugged in and it could be practical to use the physical medium already linking vehicle and EVSE, namely, the power cable. Power line carrier (PLC), where data is carried on a conductor, is the technology primarily explored by EDISON and the standards. It has been chosen in EDISON for a scenario where EVs would implement an I/O board, as described in Section 15.4, and would not have any permanent wireless network connection. A RENESAS chip is installed using a proprietary PLC technology.

The two standards investigated by EDISON, IEC 61851 and IEC/ISO 15118, both concentrate on using a wired medium but have different focuses on the EV-to-EVSE communication. The communication can, for AC charging using an on-board charger, be divided into initial signaling as described in IEC61851-1 and a high-level protocol-based communication, which is going to be standardized in ISO/IEC 15118.

The initial signaling in IEC 61851 has the purpose of indicating the state of operation between the EV and the EVSE.

State A—No vehicle connected
State B—Vehicle connected, not ready for energy flow
State C—Vehicle connected, ready for energy flow, ventilation not required
State D—Vehicle connected, ready for energy flow, ventilation required
State E—Vehicle connected, charge spot fault
State F—Charge spot not available for action

The EVSE will also be able to signal the maximum charging current back to the EV, in order to protect the EVSE’s circuit breaker, allowing for simple load control by an external energy controller or operator.

A high-level IP-based communication protocol, as part of ISO/IEC 15118, would be required for more sophisticated services, including exchange of contract-ID, charging schedules, charging status, and value added services.
15.5.2 Interface Connecting EVSE to Fleet Operator

With the predicted increase in electric vehicle penetration in the coming years and the ever increasing number of players in this field, the use of standards, especially for communication, is one of the primary resolutions of the EDISON project.

For the connection between EVSEs and the fleet operator, the well-tested IEC 61850 standard was chosen. In a bold move, mainly to ease interoperability between parties and facilitate quick prototyping, the traditional MMS standard (ISO 9605) was abandoned in favor of RESTful web service.

15.5.2.1 IEC 61850 Using REST Services. As illustrated in the IEC 61850 section the data model is a hierarchical tree structure and in order to be able to navigate this model, every element has a path that uniquely identifies its position within the structure. All paths are absolute, meaning that they list every element from the root of the structure to the element in question—exactly as seen in a file system and as illustrated in Figure 15.13.

Traditionally, the IEC 61850 standard is paired with a communication standard called the manufacturing message specification (MMS), which is extensively used in some industries where it is also known as ISO 9605. Being a binary protocol, MMS requires a detailed understanding just to get started, unless of course one uses a prebuilt API. Unfortunately, only proprietary solutions seem to exist, which further hinders interoperability. In order to better facilitate the communication among components in EDISON, an implementation was developed which enabled the use of IEC 61850 through so called RESTful web services. Apart from the academic exercise, it had the added benefit of allowing IEC 61850 enabled communication across virtually every known computer platform with little effort, improving the interoperability between parties in the project.

The cornerstone in this mapping from IEC 61850 to REST lies in the resemblance between the reference path and the URL scheme used by the HTTP protocol on which REST is based. REST, which is short for representational state transfer, was first introduced in the doctoral dissertation by Roy Fielding in 2000 [8]. Fielding is a coauthor of the HTTP protocol on which the World Wide Web is built and is a cofounder of the Apache Web Server project, the most widely used web server in the world.

![Diagram](image)

**Figure 15.13.** Illustration of the reference path structure for an IEC 61850 element.
Unlike the well-known SOAP services, the RESTful web services do not follow a specific standard, but rather a set of guiding principles central to which is the fact that data should be exposed as a resource. This principle closely adheres to the HTTP protocol; in fact, URL is short for uniform resource locator. In its simplest form, data is retrieved from a REST service by issuing an HTTP GET request for the URL representing the data one wishes to retrieve. Using this approach, access to the measurement of Figure 15.13 is a simple matter of retrieving a piece of XML from the URL http://hostname/EVSE1/MMXUI/Tot magg, resulting in the following: 

\[ \text{<DA Name="f" Type="FLOAT32" Ref="EVSE1/MMXUI/Tot.W.mag.f">0.5</DA>} \]

Since REST services put no restrictions on the format used for transporting the data, it is completely at the developer’s discretion to use whatever he/she deems suitable. If a file transfer is needed, which the IEC 61850 standard allows (e.g., for transferring configuration files or perhaps performing firmware upgrades), binary data could be the preferred option. In the case of the EDISON REST implementation, the basic format chosen is XML because it allows the relaying of hierarchical data, which means that any portion of the data model could be transferred in a single request. This has some added benefits when clients are discovering devices on the server because it allows them to retrieve the complete setup in a single request, without prior knowledge of the system. The use of IEC 61850 and REST is described by Anders Bro Pedersen et al. [9].

15.5.2.2 The Session Initialization Protocol. REST has inherited many of the benefits from the HTTP protocol, but unfortunately also suffers from one of its main drawbacks when used in a decentralized domain, which is the case with EVSEs: it is client/server based. Because many EVSEs will be attached to either private Internet connections, mobile uplinks, or the like, one cannot expect them to be reachable at a fixed network address as illustrated in Figure 15.14. One solution,
the one we propose in the EDISON project, is to use the *session initiation protocol* (SIP), which was designed for use in IP-based cellular systems to solve such issues. The use of SIP has been explored by Bernhard Jansen et al. [10].

SIP, which dates as far back as 1996, is an open and incredibly flexible protocol whose primary purpose is to allow clients to locate and reach each other over the Internet. When an SIP-enabled user agent starts, it contacts an SIP registrar to register its location. When another user agent on the network needs to reach a particular user agent, it does not need to know the location of the other party in advance. Instead, it simply sends an INVITE message to the SIP proxy of its SIP domain. If the inviting user agent and the invitee are in the same SIP domain, the SIP proxy contacts the location service connected to the SIP registrar with the name in the INVITE message to look up the contact’s details and then contacts the invited user agent by forwarding the INVITE message. Using the SIP proxies, the session is negotiated and set up between the user agents who, as a result, are provided with the information needed to create a point-to-point connection. Figure 15.15 illustrates the message sequencing for initializing, reinitializing, and closing an SIP session.

![Diagram of SIP message flow](image_url)

**Figure 15.15:** (a) SIP INVITE sequence diagram to establish an SIP dialog and a TLS/IEC 61850 session; (b) SIP reINVITE to reestablish a TLS/IEC 61850 session and (c) closing the SIP dialog.
Once the session has been initiated and the direct connection established, any type of traffic can be tunneled through. Because SIP builds on many of the same technologies as the HTTP protocol, it is also capable of using an identical security mechanism such as transport layer security (TLS) for encrypting the traffic.

Because SIP separates signaling and media transport, the media sessions are created and closed between requests. Most of the resources otherwise associated with keeping multiple connections open can therefore be freed. The SIP dialog, however, is kept open throughout the entire charging session and allows a quick reestablishment of a media session. As SIP dialog is connectionless, this is very resource effective. This helps to greatly improve the scalability, and effectiveness, allowing the EVPP to aggregate even more vehicles and keep communication costs low.

SIP allows the user agents in the network to be directly connected, but it does not handle barriers such as firewalls and the network address translation (NAT) often found in routers. To overcome these issues, the SIP protocol can be extended with additional technologies, such as the session traversal utilities for NAT (STUN) and the traversal using relay NAT (TURN).

Throughout the EDISON project great effort has been put on using standards for communication, such as SIP, TCP/IP, TLS, and IEC 61850. In this regard the SIP is considered as highly suitable to provide control and data communication between EVSE and the EVPP. As mentioned, the use of the RESTful approach helps to facilitate a much more versatile interface to the IEC 61850 server, but like all client–server communication, some drawbacks, one of which is the ever present issue with firewalls. By combining IEC 61850 and REST with the use of the SIP protocol and NAT traversing techniques such as STUN or TURN, these issues can, to a large extent, be overcome. This allows SIP/IEC 61850 enabled EVSEs a seamless and scalable integration into an EVPP system, regardless of their location or network connection.

15.5.3 Interface Connecting EV User to Fleet Operator

For intelligent EV charging to be successful, the adherence to the EV user’s driving requirements is key. User requirements can range from a general target state-of-charge for the EV to specific requirements such as having the EV at a certain state-of-charge at a certain time. The latter can be important for the user if, for example, he/she wants to leave exceptionally early the next day or go on a long trip.

To explore ways of communicating with the user, a couple of user interface prototypes, both for desktops and mobile phones, are under development within the EDISON project. The desktop interface has the form of a web site and allows the user to sign his/her vehicles up for fleet operator controlled charging, monitor the charging history, and set user specific preferences. The mobile phone interfaces can be divided into two categories: SMS and Internet based.

The SMS-based user interface enables the widest coverage, as most users have at least an SMS capable mobile device. The user then always has the ability to send
a status request SMS, for example, the text "?" to a certain number, to which the fleet operator will reply via an SMS gateway, providing the latest information about the state-of-charge. Additionally, the user might receive an SMS when plugging in the EV, containing an offer for doing smart charging.

The Internet-based interaction is either in the form of a device-specific application or a web site. While device-specific applications probably offer the richest user experience and allow for push notifications to the device, a mobile-specific web site can reach a broader spectrum of devices. In the prototypes of these interfaces currently under development, the user can monitor the charging process, see the fleet operator’s current availability prediction for the EV, and update the estimated plug-out time to meet his/her requirements, while still allowing for smart charging. It is important that the user always understands what the server-side system is allowed to do, and what state-of-charge he/she can expect when the vehicle is needed.

Apart from desktop and mobile phone-based user interfaces, the EVSE and the EV could also have a user interface, which could offer similar functionality as the mobile phone interface (due to the similar screen size). A solution for these could be to simply host a browser component which displays web pages served by the fleet operator, thus allowing for communication with any fleet operator. Alternatively, device-specific applications could be used to communicate with the fleet operator via web services; this would, however, require standardization of the fleet operator APIs and would make support for different fleet operators difficult.

All of the above-mentioned user interfaces rely on the fleet operator to provide the data and do not therefore require the EV to have a wireless Internet connection.

15.6 DEMONSTRATION

This section shows some of the interfaces developed in EDISON to test and illustrate smart charging.

15.6.1 End-to-End Demonstration: From EV to Operator Panel

The EDISON VPP operator panel has been developed to demonstrate the operation of an EVPP and is implemented as a Microsoft Silverlight application hosted by a web browser. A screenshot of the panel is shown in Figure 15.16.

The interface features the following areas: "1" is a full list of EVs managed by the EVPP followed by a fleet summary in "2." When an EV is selected in "1," its status and data are displayed in the right portion of the interface. While "3" displays the selected EV's last known status, "4" displays a subset of the static information on the specific EV. The EV's location is available to the EVPP when the EV is plugged in and can be seen in "5." The graphs labeled "6" through "8" display information for a selected 24-hour period. Here "6" displays the availability periods...
Figure 15.16. EDISON operator panel screenshot.

of the EV, that is, the periods where the car is parked and plugged in. Graph “6” shows both the recorded and predicted availability of the vehicle, illustrated by the upper and lower horizontal bars. Graph “7” displays the energy prices for the time period and “8” shows the charging schedules, which have been generated by the EVPP and are sent out to be executed by the EVSE.

The interface screenshot demonstrates that the EVPP can be connected to a set of real or virtual cars each with their own unique patterns and characteristics, and generate charging schedules that avoid charging at expensive hours. The latter can be seen by comparing prices “7” and charging periods “8” on the screenshot. The EVSE panel is also useful in retrieving and visualizing historical data.

15.6.2 Physical Demonstration Assets

The island of Bornholm has been chosen as a test site for demonstrating the technical solutions developed by EDISON. As an island, it is an isolated environment capable of running independently from the surrounding power system and it has a suitable composition of renewable energy sources, which are representative for the whole of Denmark. It is on Bornholm that the ICT architecture and its components will be
put to the test in managing smart charging for EVs of various brands and types. Figure 15.17 shows the main physical assets that will be used to validate smart charging on the island of Bornholm.

Since at least one brand of EVs (converted Toyota Scion) will support vehicle-to-grid (V2G) technology, the EDISON island demonstration can also cover advanced EV services, in which power is delivered back to the grid. Finally, roaming scenarios can be tested on the island using different EV and EVSE combinations.

Although lessons learned from the physical demonstrations will be an important part of EDISON, the project should also analyze integration scenarios where very high numbers of EVs are introduced on Bornholm. For practical reasons this requires simulations, which are the topic of the next section.

### 15.6.3 A Large-Scale Virtual Fleet

Potentially massive roll-outs of electric vehicles have been predicted within the next few years and already several major automotive manufacturers are trying to get a head start: most with their individual visions for the future, what it may bring and what may be chosen as the de facto standards. Some are sticking with one type of
charging socket, others another. Some are leaning toward battery swapping while others are set on fast charging and so on and so forth. On top of all the above-mentioned uncertainties, there are also questions that need to be answered regarding the impact of all these EVs on the power grid. How will the grid handle the extra load? Where and when will this dynamic load be connecting geographically? Where are the potential bottlenecks in the distribution system? How do we prevent them from occurring? The list goes on.

Common for all these questions is that they represent potential problems, for which we need a solution before the problems actually occur and the only way to test this “in practice” without causing a disaster is through the use of simulations.

For the EDISON project a very flexible EV simulation system was developed as an extension to the IEC 61850 server described earlier.

By using geographic data, demographic statistics, and recorded vehicle data from real-world experiments, large groups of virtual EVs can be created with behaviors closely resembling people’s current driving habits. Because the grid impacts resulting from increased EV penetration is an important topic, it was not enough to simply simulate the consumption of a fleet of vehicles. Instead, using route data obtained from online services, the vehicles were simulated in real time as they would be driving around on the island—see Figure 15.18. In practical terms, it would have been enough to simply calculate the consumption from a given trip and then move the vehicles around, but the added effect of having moving vehicles makes for a very audience friendly demonstration.

Because the simulation runs as an extension of the IEC 61850 server, all devices are automatically made available through the IEC 61850 RESTful interface, allowing the VPP to actively aggregate the whole fleet as if they were real EVs—see Figure 15.19.

15.7 CONCLUSION AND FUTURE WORK

This chapter has explored the technologies used by the EDISON project in terms of communication standards, components, and stakeholder interfaces.

Initial testing indicates that the IEC 61850 and IEC 61851 standards are valid candidates for EV integration. Also, the upcoming ISO/IEC 15118 standard could prove very beneficial for promoting advanced EV services as well as roaming and should be followed carefully. The chapter also puts emphasis on a few selected components that were developed by EDISON partners to demonstrate smart charging. The software and hardware developed for the vehicle, charging spot, and fleet operator will serve as input to standardization work.

Another topic covered by the chapter is the specific protocols that will enable communication in EDISON. In this context we looked at how HTTP based web services and the SIP protocol fulfill certain requirements of interoperability, security, and scalability. Transport layer security (TLS), a technology used in such areas as Internet banking, has been suggested for improving security.
Figure 15.18: Simulated commuter route across the Island of Bornholm.
The chapter concluded with a few examples of how EDISON aims to prove and validate its work through a set of demonstrations. This includes a field test of an EV fleet on the island of Bornholm and the use of large virtual fleets simulated in software.

A suitable and standardized ICT architecture, which has been the focus of this chapter, is a vital piece in EV integration and a key part of EDISON. Other research areas such as battery technologies, fast charging, and distribution grid impacts are, however, equally important and are covered by partners in the project. Only by covering all topics relevant to society’s transition to electric transportation can EDISON achieve its goal of aiding and promoting the cause of the electric vehicle.

The EDISON project will continue with its V2G research and evaluate which standards best support this type of service. While the IEC 61850 schedules presently used support V2G, the OpenV2G project [11], associated with ISO/IEC 15118, and the V2G project [12], led by Professor Willett Kempton from the University of Delaware, both represent possible alternatives and should be studied thoroughly. The progress of EDISON is continuously updated on the project web page.

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D  Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves

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Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves

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Abstract— With the increased focus on Electric Vehicles (EV) research and the potential benefits they bring for smart grid applications, there is a growing need for an evaluation platform connected to the electricity grid. This paper addresses the design of an EV test bed, which uses real EV components and communication interfaces, to be able to respond in real-time to smart grid control signals. The EV test bed is equipped with a Lithium-ion battery pack, a Battery Management System (BMS), a charger and a Vehicle-to-Grid (V2G) unit for feeding power back to the grid. The designed solution serves as a multifunctional grid-interactive EV, which a Virtual Power Plant (VPP) or a generic EV coordinator could use for testing different control strategies, such as EV contribution to regulating power reserves. The EV coordination is realized using the IEC 61850 modeling standard in the communication. Regulating power requests from the Danish TSO are used as a proof-of-concept, to demonstrate the EV test bed power response. Test results have proven the capability to respond to frequent power control requests and they reveal the potential EV ability for contributing to regulating power reserves.

Index Terms— Electric vehicles, Test Bed, Regulating power, Virtual Power Plant

I. INTRODUCTION

THE Electric Vehicles and Plug-in Hybrid EV (PHEV) are expected to play an important role in the future power system. Within smart grids research, electrical transportation has a complementary role in the overall system management of energy and power [1]; moreover the European target on reducing CO₂ emissions and increasing penetration of renewable energy are among the major drivers for the research [2].

The energy storage capability is the key factor for smart grid applications of EV in power system. When parked and plugged into the grid, EV are expected to either charge intelligently, or discharge feeding power back to the grid [3]. In the latter case, EV would enter a mode known as Vehicle-to-Grid (V2G), permitting the provision of several grid services [4]. In general, if the individual EV can be intelligently managed, a large number of such vehicles can become an asset in the future power system. The charging process could be controlled by modulating the charging power, as well as the discharging process, by enabling the V2G mode when there is a need from the grid [5]. Many projects are addressing the aforementioned EV operation, as coordinated charging using different simulation tools. In [6], the authors analyze, through dynamic simulations, the potential daily profits for EV users, with the provision of regulating power. In [7], the authors studied the benefits offered by EV for facilitating the integration of large scale wind power in Denmark; EV fleets are modeled in a simulation platform as storage units when charging or as small generators during V2G operation. Galus et al. in [8] presented a method for tracking secondary frequency control using groups of PHEV and a simulation platform to simulate an EV aggregator.

The participation of EV in regulating power schemes is possible using an aggregation entity for EV coordination. This is done in the Danish EDISON project [9]-[10], where the contributors proposed a centralized coordination solution for an efficient integration of EV in the power system. The aggregation technology is based on the Virtual Power Plant (VPP) concept [11], where the Edison VPP is the EV coordinator.

Evaluating the contribution of an EV for regulating power reserves in a VPP framework, where a huge amount of communication and hardware interfaces are involved, gives raise to the need of new grid-interactive evaluation platform.

This paper describes the implementation phases of an EV test bed, working under the coordination of a VPP and contributing in regulating power reserves, as secondary frequency control [12]. A real regulating power request from the Danish Transmission System Operator (TSO) is processed by the VPP and sent in form of a charging/discharging power schedule to the EV test bed.

Test results performed using the EV test bed show that an EV is in fact capable of real-time communication with a VPP and can quickly react to contribute to grid power reserves.

II. ELECTRIC VEHICLES FOR SMART GRIDS

The interaction between EV and the electric power system is only possible if the vehicles can connect to the electrical...
An effective interaction between EV and grid requires the combinations of different factors such as:

- Grid interactive vehicle architectures;
- Controllable charging/discharging operation;

### A. Electric vehicle architectures

Among different types of hybrid electric vehicles and pure electric vehicles, a general distinction is based on their ability to plug-in. In this work, non plug-in hybrid vehicles will be disregarded, as an interconnection with the grid is not possible.

This section lists the system architectures capable of charging using the grid [13]. There are mainly two classes of plug-in EV: plug-in hybrid EV (PHEV) and battery-powered EV. An overview on the different architectures is depicted in Fig. 1.

In the PHEV class, three variants have been developed so far:
- Series-parallel hybrid
- Series hybrid
- Parallel hybrid

The main difference among the topologies is the drive system used and the interconnection of its components, before the power is transferred to the wheels.

In the series-parallel hybrid vehicle, Fig. 1 (a), the system is designed to operate both in a series or parallel configuration. The reconfigurable system is made possible by the use of a planetary gear, which is the mechanical coupling (MC) for the three machines. In the series hybrid vehicle, Fig. 1 (b), the electric traction system and Internal Combustion Engine (ICE) system operate in a series connection. In sequence, the ICE is coupled with a generator (Gen.) which generates the electric power for recharging the battery, the battery then supplies an electric motor driver to transfer power to wheels. In the parallel hybrid vehicle, Fig. 1 (c), the ICE and electric motor (EM) operate in parallel mode, where the ICE supports the electric traction at certain points of the driving pattern, e.g. when higher power is needed to the wheels.

In the battery-powered EV class, Fig. 1 (d), the drive system is realized using only an electric motor and a motor driver. Therefore the only energy source is the battery pack.

In this work a battery-powered EV is the architecture chosen for the EV test bed implementation.

### B. Controllable charging/discharging operation

All plug-in EV are able to absorb power from the grid while charging their battery packs. The controlled charging or discharging (V2G) process can be achieved using different infrastructure concepts, such as home charging or public charging stations [14]. According to the IEC 61851 standard [15], the most common power rates for domestic and public charging are depicted in Table I.

<table>
<thead>
<tr>
<th>AC current</th>
<th>AC voltage</th>
<th>Grid connection</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 A</td>
<td>230 V</td>
<td>single phase</td>
<td>2.3 kW</td>
</tr>
<tr>
<td>16 A</td>
<td>230 V</td>
<td>single phase</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>32 A</td>
<td>230 V</td>
<td>single phase</td>
<td>7.4 kW</td>
</tr>
<tr>
<td>16 A</td>
<td>400 V</td>
<td>three-phase</td>
<td>11 kW</td>
</tr>
<tr>
<td>32 A</td>
<td>400 V</td>
<td>three-phase</td>
<td>22 kW</td>
</tr>
</tbody>
</table>

All power rates, regardless of charging or discharging, are characterized by an AC current, usually 16A or 32A, and based on the grid connection type, single-phase or three-phase.

In this work a charging/discharging power rate of ± 2.3 kW is used for the experimental validation.

### C. Planned EV test bed operation with Virtual Power Plant

The EV system architecture is planned to respond to different control signals from a centralized EV coordinator.

The control signals for the vehicles can be generated by a VPP and based on different variables such as the power system frequency, the market spot price and others.

In this paper, the centralized control concept for EV fleet management as described by Binding et al. in [10] is used as a study framework. The EV test bed operation is planned within the VPP framework depicted in Fig. 2. Different interfaces have been defined to establish communication between the Edison VPP and other entities in the architecture. While a
generic VPP can aggregate and control various distributed energy resources (DERs), e.g. combined heat and power units (CHPs), PV plants, wind turbines, medium/large consumers, other power units and smart houses, in this paper, only EV are considered.

An interface with the TSO is defined to receive the activation commands for accepted regulating power reserves contracts.

An interface with the Distribution System Operator (DSO) is also defined to collect the grid status for the location of every connected EV. Grid constraints are considered at this interface, to ensure that the charging/discharging operation complies with power quality issues. In addition, the metering information for accounting is also collected via the DSO interface.

Fig. 2. EV test bed operation in a Virtual Power Plant framework

The transaction interface with a billing provider is used to perform billing to the resources providing regulating services.

In this paper, the EV-VPP interface is implemented to establish communication between the VPP and the EV test bed. The control requests for the EV test bed are generated from the VPP, based on the grid needs of regulating power reserves of the TSO.

III. TEST BED IMPLEMENTATION

Designing an EV test bed for testing the potential EV operation with a VPP was performed in two phases:

- Planning the EV test bed architecture
- Dimensioning the EV components

A. Planning the EV test bed architecture

With reference to the EV architectures described in Section II, a battery-powered EV architecture was the choice for the EV test bed implementation. The main reasons for choosing this architecture is that with a pure battery EV, zero emissions can be achieved during driving [16], while grid interaction is more meaningful, due to a larger storage capacity.

In a battery-EV the following components can be considered:

- a battery pack
- a battery charger
- a BMS
- a three-phase motor driver
- an electric motor

For the scope of the study, the three-phase motor driver and the electric motor are not needed, therefore these two components were not considered in the development.

Since with the architecture of Fig. 1 (d), the V2G operation is not possible, this was enhanced by adding a V2G unit which could operate in a complementary way to the charger. The implemented EV test bed architecture is shown Fig. 3.

![Fig. 3. EV test bed architecture](image)

The battery pack is interfaced to a battery management system (BMS), which monitors its status.

The charger is designed as an AC/DC converter, directly connected to the main grid, by means of a three phase cable connection; while the V2G unit is made of a single phase DC/AC inverter.

It is worth noticing that, since the aim of the EV test bed is to emulate a real EV connected to the grid, all EV components were dimensioned according to realistic EV energy and power levels.

B. EV test bed components

The design of the battery pack took into account the following requirements:

- Common designs of battery-EV [17][18]
- V2G operation requirement

The choice of a battery technology to use for the test bed was based on the analysis of current market trends for EV. Some consulting companies, e.g. Frost & Sullivan [19], foresee more than 70% of EV in 2015 to be powered by lithium-ion (Li-ion) batteries. Compared to other battery technologies, Li-ion batteries offer a greater energy-to-weight ratio, greater power levels and low self-discharge when not in use [16]. For the reasons mentioned, a Li-ion battery was the choice for the EV test bed.

The electrical features of the battery pack were chosen considering common designs of EV battery packs. Generally
battery-EV have battery pack voltages in the range of 300-400 V and a battery capacity of at least 10-15 kWh. A battery pack was designed integrating 110 Li-ion series connected battery cells, which leads to a total nominal pack voltage, $V_{pack}$, of 363 V. Each cell has nominal voltage $V_n$, of 3.3 V and nominal capacity $C_n$, of 40 Ah.

Based on the nominal parameters, the following expression is valid for calculating the nominal battery energy:

$$E_n = V_{pack} \cdot C_n = N \cdot V_n \cdot C_n$$  \hspace{1cm} (1)

where $N$ is the number of cells.

The requirement of V2G operation, a DC/AC power converter with input DC voltage in the range of 250 – 500 V was used. The rated output power of the V2G inverter is about 4 kW, which leads to a maximum generated AC current of around 16 A. The V2G inverter is also equipped with an internal transformer, which serves as galvanic isolation.

A battery management system (BMS) is linked to the battery pack. The main function of the BMS is to ensure a safe operation of the battery pack during charging or V2G operation. It estimates the SOC information which is used by VPP and monitors the battery voltage, current and temperature.

The charger was designed as a single-phase AC/DC. The output voltage $V_{dc}$ was dimensioned using the empirical formula shown below, according to [20]:

$$V_{dc} = 1.25 \cdot V_{pack} = 453 \text{ V}$$  \hspace{1cm} (2)

The current $I_{dc}$ on the battery side is dimensioned of 10 A at full load, which leads a charging power of about 4.5 kW.

The implemented test bed with integrated EV components is depicted in Fig. 4.

IV. Communication and Control with VPP

As previously mentioned, the EV test bed was designed to operate as part of a centralized aggregation framework, under the direct control of a VPP, as described in [21]. For the purpose of future research, it will be possible, in any case, to adapt the software system in order to e.g. test decentralized control schemes.

![Fig. 5. EV test bed communication and control architecture](image)

To facilitate centralized coordination, the VPP-to-EV interface was implemented in accordance with the communication and control architecture depicted in Fig. 5.

The communication is based on the well-established IEC 61850 standard [22]. As an academic exercise and in the attempt to promote the use of existing web standards in power system communication, the IEC 61850 standard was mapped to HTTP/REST. This work was presented in details in [23].

The VPP used for this paper was designed by Pedersen et al. [23] and has been used for generating and sending power schedules, in response to the requirements for regulating power reserves specified by the TSO.

Though used for an EV test bed in this case, these schedules are simply based on positive/negative power requests with an associated time stamp. For this reason, they are potentially applicable to any type of Distributed Energy Resource (DER) [24].
A. IEC 61850 Server and Module

The server, which was developed in compliance with the IEC 61850 standard, is designed based on a modular plug-in architecture, in order to facilitate an easier adaptation and installation of new devices of virtually any type [23].

A device specific plug-in, or IEC Module, was implemented, in order to enable direct control of the test bed from the VPP, as well as to facilitate the collection of battery status information along with any other measurements.

Because the charger and inverter are two separate pieces of hardware connected to the same battery, an algorithm was written into the plug-in module to guarantee the mutually-exclusive operation of the connecting relays. This prevents the simultaneous operation of both devices.

Another communication link is established between software plug-in and the BMS to extract the state-of-charge (SOC) information from the battery.

B. Charging

As indicated by Fig. 6, there is no direct control link between the IEC Module and the charger; this is because the charger has no communication interface for remote control. For the purpose of this paper, the charger is fixed to a fixed power rate and is coupled or decoupled from the battery by means of a DC relay, which is controlled via RS232, as illustrated in Fig.

As previously mentioned, the charger and inverter are both connected to the battery pack using two mutually exclusive relays. In order to ensure that the devices have exclusive “access” to the battery, a simple timing scheme was used in the IEC Module. As depicted in Fig., a time gap was added between two switching events to ensure a safe transition.

C. V2G

The coupling of the V2G inverter is achieved by means of an identical DC relay as for the charger. Under V2G operation, the generated power level is controllable and this is managed through an attached communication hub. The same hub implements an HTTP/JSON web interface. A more detailed illustration of the V2G architecture used for the EV test bed is depicted in Fig. 8.

D. Battery Status Information

The real-time status of the battery is monitored by the BMS. The BMS information is acquired by the IEC Module using RS485 based serial communication link. By means of this link, all battery data can be extracted as a set of values and made available to the VPP via IEC 61850 for detailed monitoring. The set of values includes:

- Battery pack voltage
- Current
- State of charge
- Temperature in different areas of the battery pack
- Remaining energy and single cell voltages

The BMS comes equipped with an RS232 port for remote monitoring of the battery pack, as well as controlling various limits/alarms. Connected to the BMS are a series of sensors, which connection are depicted as a series of smaller wires in Fig.
V. EXPERIMENTAL RESULTS

The EV test bed participation in regulating power reserves was tested considering the regulating power required for secondary control, by the Danish TSO, on the 1st of January 2009 [25]. The regulating power profile sent from the TSO to the VPP is given in 5-minutes average MW values as shown in Fig. 10(a). The target regulating power is derived by the sum of all up and down regulation requests sent out by the TSO to an array of providers in the same 5-minutes. The target anyway does not reflect the exact need of the system but rather the value is used to drag the providers in the right direction. Nevertheless, the target value is a very good approximation to the real-time need of regulation reserves.

A new schedule, related to the TSO power target, was generated by the VPP every 5-minutes, and sent to the EV test bed. The regulation was tested in the time interval 16h30 to 19h30. The schedule is shaped as ±2.3 kW power requests with time stamps, indicating the activation/deactivation time of charging and V2G mode, Fig. 10(a). Since each EV has a very small capacity compared to the grid needs, it was assumed that the VPP meets the TSO target by aggregating a number of simulated EV. The EV system response, Fig. 10(b), is taken measuring the electric power flow at the point of connection.
common coupling (PCC) of the EV test bed with the grid. The power was recorded with 1 minute sampling time. Test results are depicted in Fig. 10(b). It is possible to observe that the EV test bed is able to react in real-time to the power schedule sent by the VPP. The measured power profile in Fig. 10(b) validates the effectiveness of the EV architecture proposed in this work. Furthermore, the SOC profile shows the energy variation in the EV test bed battery, during the regulation service. The EV test bed started to contribute to regulating power service with an initial SOC of about 0.5 or 50%.

VI. CONCLUSIONS

Testing the capabilities of EV for smart grid applications requires the development of adequate evaluation platforms. In literature it was demonstrated that EV can potentially operate under a number of coordination schemes, including the participation in regulating power reserves. While this was extensively presented by simulation scenarios, in this paper, a real implementation of regulating power reserve performed by a full-scale EV test bed was presented. The test bed was designed to flexibly interact in real-time with an EV coordinator and the electricity grid, under different coordination concepts. To do so, real EV components and communication interfaces were used, that make possible an end-to-end interaction with a VPP. The implementation of an EV test bed from scratch enabled the management of the single components involved in the EV system: charging/discharging units and BMS. With the implemented communication and control architecture it was possible to establish a stable communication between the EV the test bed and the Virtual Power Plant.

The potential offered by EV for regulating power was demonstrated testing the EV test bed hardware and software interfaces. An array of regulating power requests (load frequency control) within a 3-hours time interval, sent by the Danish TSO on the 1st of January 2009, was used as study case. The TSO target values were converted to an EV compatible schedule by the Edison VPP and sent down to the EV test bed among the other simulated EV. Test results revealed the potential capability of EV to respond in real-time to different charging/discharging requests based on different coordination plans. Further investigations will be performed for evaluating the reliability of the communication involved, when several fleets of EV are simultaneously coordinated.

ACKNOWLEDGMENTS

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9. CORE PUBLICATIONS

E Prediction and Optimization Methods for Electric Vehicle Charging Schedules in the EDISON Project

This paper was published in the Proceedings of the IEEE PES Conference on Innovative Smart Grid Technologies (ISGT), 2012, Washington, D.C, USA.
Prediction and optimization methods for electric vehicle charging schedules in the EDISON project

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Abstract—Smart charging, where the charging of an electric vehicle battery is delayed or advanced in time based on energy costs, grid capacity or renewable contents, has a great potential for increasing the value of the electric vehicle to the owner, the grid and society as a whole.

The Danish EDISON project has been launched to investigate various areas relevant to electric vehicle integration. As part of EDISON an electric vehicle aggregator has been developed to demonstrate smart charging of electric vehicles.

The emphasis of this paper is the mathematical methods on which the EDISON aggregator is based. This includes an analysis of the problem of EV driving prediction and charging optimization, a description of the mathematical models implemented and an evaluation of the accuracy of such models. Finally, additional optimization considerations as well as possible future extensions will be explored.

This paper hopes to contribute to the field of EV integration by coupling optimized EV charging coordination with the EV utilization predictions on which the former heavily relies.

I. INTRODUCTION

Besides offering a means of cleaned transportation, the electric vehicle (EV) represents a high-powered, quick responding, controllable load that can adjust its charging behavior to the day-ahead energy prices and even participate in ancillary service markets.

The Danish EDISON project [11],[12] has been launched to explore the above potential by investigating topics relevant to EV integration and to demonstrate how the charging and possible discharging of electric vehicles (EVs), if handled intelligently, can yield benefits to the EV owner, the grid and society.

A wide range of different EV integration concepts are already being investigated in numerous similar projects. Integration concepts typically differ in what needs the EV is used to fulfill in the power system and what mechanisms, designs and technologies are used to control or influence the EVs interaction with the grid.

The approach used in EDISON is having an Aggregator entity control the interaction between an electric vehicle fleet and the electrical grid to facilitate 'smart charging'. The EDISON aggregator is demonstrated both towards real EVs and a simulated fleet.

The aggregator software implemented in EDISON relies on a set of algorithms in order to predict the charging availability of the fleet and minimize the charging cost based on day-ahead energy markets. The main focus of this paper is on the description and evaluation of a prediction method using exponential smoothing. Besides minimizing the charging cost, a set of additional considerations imposed by the owner of the vehicle, the distribution grid and the EV battery should also be added to the optimization.

The remainder of the paper is organized as follows. Section II will describe work by IBM and the University of Delaware relevant to the EDISON project and this paper. In section III will describe the mathematical problems that will be addressed by the models described in sections IV and V. Sections VII and VIII will present results based on the empirical data used. Section IX will introduce regulation services on top of smart charging. Finally, section X will summarize the findings of the paper.

II. RELATED WORK

Sundstrom and Binding have, in a set of papers, focused on coordinated EV fleet charging. In [13] the authors use linear and quadric programming to minimize charging costs. In [8] the same authors propose an optimal charging method where the aggregator is aware of the grid constraints. In a third paper [14] Sundstrom and Binding investigate how the charging planning of an aggregator can be made to meet user requirements.

This paper adds to these papers by focusing on the availability prediction and by suggesting additional considerations and constraints.

According to research by Kempton et al. from the University Of Delaware (UD), an EV would be parked 95% of the time and would thus represent a vastly underutilized resource if its potential for servicing the grid is not used [15],[16]. From the same research group, Kamboj has developed algorithms that calculate an electric vehicles ability to participate in frequency regulating services while considering the energy requirements and time constraints of the EV owner [17]. The EDISON Aggregator software could borrow from the experiences of UD and there are plans to add regulating services to the objectives of the EDISON aggregator software.

III. ANALYSIS OF THE PROBLEM

For an EV to adjust its charging behaviour according to day-ahead energy prices and still meet the energy demand of the individual EV owner, mathematical models need to be developed. A major concern is that reliable data of EV driving
behaviour is hard to come by. Some studies have been conducted but most of them are geographic and demographically biased.

The AKTA data [19] was originally collected in a collaboration between the city of Copenhagen and the Technical University of Denmark in order to investigate the driving habits of people living in the capital. The AKTA data, which is used in this study, are collected by means of GPS where a total of 360 vehicles were followed from 14 to 100 days in 2001 - 2003. The AKTA data is biased towards driving patterns similar to everyday driving in the greater Copenhagen area. The data is incomplete in that some observations are missing. The data have been filtered to include only the observations which have been plugged in during night time for more than ten days during the period of the trial. There are 205 observations left in the sample after this filtration.

The present study is aiming at developing a robust framework not too sensitive to the errors of prediction. It is assumed that the day-ahead energy prices are known. It will be investigated how to model the day-ahead demand of an EV owner and using the just stated estimation along with the day-ahead energy prices to calculate the optimal charging schedule for a single EV.

The overall framework used in the present proceeding is depicted in figure 1. At the individual level every EV will have a static energy demand until enough data has been collected. Once enough historic information is available a prediction model will be developed. The prediction model and the optimization model have a low coupling. This makes it possible to schedule 24 hours ahead.

Consider figure 2. The interval available for charging to be passed to the optimization model is the period between the maximum of the plugin prediction interval and the minimum of the plugout prediction interval.

**Fig. 1. Meta model**

**Fig. 2. Stopover duration.**

An exponential smoothing model for estimating plugin intervals will be used. The model is given by the recursive equation

\[
X_{n+1} = (1 - \delta)X_n + \delta S_n, \tag{1}
\]

where \(\delta \in [0,1]\) is a fixed parameter, \(X_1 = S_1\) and \(S \in \mathbb{R}^n\) is historic data for a given vehicle.

Preprocessing the data to remove outliers will be necessary for sparse data. Let \((\mathbb{R}^n, \| \cdot \|)\) denote the usual n-dimensional Euclidean space equipped with the usual norm, i.e.

\[
\|x\|^2 = \sum_{i=1}^{n} x_i^2, \quad x \in \mathbb{R}^n.
\]

The variance of a sample \(x \in \mathbb{R}^n\) is thus given by

\[
\sigma^2 = \frac{1}{n-1}\|x - \mu\|^2,
\]

where \(\mu\) is the mean of the sample and \(\mathbb{I}\) is the identity element in \(\mathbb{R}^n\). From now on the identity element will not be written when vector-scalar addition occur. Here \(x\) is interpreted as the time series of historic data for a given EV. It is assumed that behaviour which deviates sufficiently from the mean is unpredictable and this leads to the following lemma, which states a criterion for an element in a sample to be "predictable". This lemma will be used for variance reduction.

**Lemma IV.1.** Denote by \(\mu\) and \(\sigma^2\) the mean and variance, respectively, of a sequence \(x_n\) of positive real numbers. Let \(x_{n_k}\) be a subsequence of \(x_n\) and let \(p\) be a fixed positive integer such that \(\mu \geq p\sigma\). Then

\[
\begin{align*}
\{x_{n_k} - \mu\} &\leq p\sigma, \quad \forall k \\
\{x_{n_k} &\in [\mu - p\sigma; \mu + p\sigma], \quad \forall k\}.
\end{align*}
\]
Proof: Since \( x_{nk}, \sigma \geq 0 \) for all \( k \) and \( x \in \mathbb{R}^n \) it suffices to consider
\[
|x_{nk} - \mu|^2 \leq p^2 \sigma^2 \iff x_{nk}^2 + \mu^2 - 2\mu x_{nk} - p^2 \sigma^2 \leq 0.
\]
This is a quadratic inequality and solving it finishes the proof of the lemma.

Consider a sequence \( (x_n) \in \mathbb{R}^n \) with variance \( \sigma^2 \) and mean \( \mu \). Let \( p \in \mathbb{N} \) such that \( \mu \geq p \sigma \). Then, for a subsequence \( (x_{nk}) \in \mathbb{R}^k \), with variance \( \tilde{\sigma}^2 \) and mean \( \tilde{\mu} \), satisfying
\[
|x_{nk} - \mu| \leq p \sigma, \quad \forall k
\]
then it is assumed that \( \tilde{\sigma}^2 \leq \sigma^2 \).

The above states that if a subsequence \( x_{nk} \) is chosen such that it is an integral number, \( p \), of standard deviations \( \sigma \) away from the mean \( \mu \), then the variance of this subsequence is bounded by the variance of the original sequence.

In [14], Sundstrom and Binding presents a linear programming model which uses time and energy margins to compensate for prediction errors. The time and energy margins are implemented by modifying the optimization constraints.

The method used here compensates for prediction errors prior to optimization by considering the variance of the predictions. This is done for time and could also be used for prediction errors of energy targets if energy was part of the prediction model.

After determining the stopover duration, the time period will be cropped in both ends depending on the standard deviation of the prediction i.e. the more unpredictable the driving behaviour, the more conservative the duration estimate.

V. MATHEMATICAL MODEL FOR OPTIMIZATION

A charging schedule defines the periods in time and charging powers at which an EV should charge its battery. The optimization algorithm is the generator of the charging schedules.

Let \( \alpha \in \mathbb{R}^m_+ \) denote the cost vector and write \( \alpha_i \) for the cost at time interval \( i = 1, ..., n \), where \( n \) is the number of time intervals, and let the length of the time interval be \( \beta_i \), where \( \beta \in \mathbb{R}_+^m \). Let \( p_j \in \mathbb{R}_+^m \), such that \( p_j \) denotes the power at which the battery is charging, \( j = 1, ..., m \), where \( m \) is the number of possible power configurations. Normally one could use the \( p \) vector as the decision variable, if \( \{0\} \) is included in the set of power configurations, but here it will be used that there exists a vector \( e \) such that \( p_j = \sum p_j e_j \) where \( e_j \in \mathbb{Z}_2 = \mathbb{Z}/2\mathbb{Z} \) for every \( j = 1, ..., m \).

The prediction model will be used to produce an estimate of the lower and upper bounds for the number \( n \).

Let \( X \in \mathbb{Z}_2^{n \times m} \), i.e. for every \( i \) it holds that \( X_i \in \mathbb{Z}_2^m \). Choose \( X \) as the decision variable and let \( f : \mathbb{Z}_2^{n \times m} \rightarrow \mathbb{R} \) be the cost function defined by multiplying every defined variable in the obvious linear fashion. While the objective is to minimize the cost, the initial model to be used is then given by
\[
\min \quad f_{m,n} = \sum_{i=1}^n \sum_{j=1}^m \alpha_i \beta_j p_j X_{ij}
\]
subject to:
\[
\sum_{j=1}^m X_{ij} \leq 1,
\]
\[
\sum_{j=1}^m \sum_{i=1}^n \beta_j p_j X_{ij} \geq E,
\]
where \( E \) is the energy required by the EV. The product of the optimization model is a charging schedule like the one shown in figure 3.

VI. VALIDATION OF RESULTS

The following example demonstrates the level of robustness of the optimization model. This will also demonstrate that the prediction model need not be very precise, which is good because it is very hard to make good predictions based on human behaviour.

Assume a given EV has an average stopover duration \( \mu \). Depending on the standard deviation \( \sigma \) of the prediction it can be determined how this influence the objective of the optimization model. Assuming that the data is normally distributed, which may or may not be the case, a sample from the normal distribution \( N(\mu, \sigma^2) \) can be used to determine how many times the linear model will produce false positive estimates, i.e. predicting an EV is ready for charging when it is not. This is done by only considering the prediction of some of the parameters of the optimization model, keeping in mind that true negatives are not considered bad estimates here. Indeed these estimates are good by construction and can be optimized further to yield less expensive results, i.e. minimizing the objective function further. However, the risk of getting false positives increases with the goal of minimizing the objective function. To see how the errors may influence the objective function, consider the surface \( w : U \subset \mathbb{R}^2 \rightarrow \mathbb{R} \) where the parameter space \( U \) is chosen to be the mean and standard deviation of a series of predictions. The height used here is the probability of the EV being ready for charging as predicted. This is expressed mathematically by
\[
w(\mu, \sigma) = P(a < x \leq b), \quad x \sim N(\mu, \sigma^2).
\]
In the current setting \( P(x \leq b) = F_x(b) \) where
\[
F_x(b) = \frac{1}{\sqrt{2\pi}\sigma^2} \int_{-\infty}^{b} e^{-\frac{(u-x)^2}{2\sigma^2}} \, du
\]
is the cumulative distribution function, it holds that
\[
P(a < x \leq b) = F_x(b) - F_x(a).
\]

Fig. 4. Probability surface.

From this it is possible to deduce bounds for mean and standard deviations from which the model works sufficiently well. Let \( V \subset U \) be the set of parameters such that \( w(\mu, \sigma) \geq 0.95 \). Then the pairs \((\mu, \sigma)\) will belong to a closed and bounded region \( V \subset \mathbb{R}^2 \).

Fig. 5. \( V \) cropped to the region \([200; 1600] \times [100; 300]\).

From this it can be concluded that predictions will get worse if:

1) For a fixed mean the standard deviation increases.
2) For a fixed standard deviation the mean decreases.

The estimator for the standard deviation of a sample \( x \in \mathbb{R}^n \) used here is
\[
\sigma = \frac{1}{\sqrt{n-1.5}} \|x - \mu\|.
\]

This estimator is not completely unbiased but it is sufficient for the current analysis.

If the data for a particular EV is not normally distributed then the above figures may look different. However it is likely that the same considerations can be made based upon the particular distribution.

VII. RESULTS

In the following the method described in the previous section will be carried out on the AKTA data. The following figure illustrates that the predictions, in general, lie in the desired region \( V \).

Fig. 6. Results cropped to the region \([200; 1600] \times [100; 300]\).

Since the data set is quite small from a statistical viewpoint, it will be shown that these predictions may lie outside the region \( V \). Consider the 95\% prediction interval
\[
[\mu - 1.96\sigma; \mu + 1.96\sigma].
\]

From this the worst case scenario (assuming estimator for \( \sigma \) is good) is that the predictions are placed in the lower part of the interval. For the data set used here there are 205 observations which have more than 10 days worth of observations. There are 13 observations which have a lower bound of the prediction interval outside the region \( V \). That is around 93.65\% of the predictions will lie in the region \( V \). It is however unlikely that all the predictions will be placed in the lower part of the prediction interval.

A example of how the optimization model performs when the variance of the predictions increases is now considered. The energy is assumed to be fixed, say \( E = 20000 \) Wh, and the prices \( \alpha_i \) have been sampled from a uniform distribution on the interval \([80; 120]\).
The possible charging periods $\beta_i$ are all assumed equal in lengths and measured in hours, i.e.

$$\beta_i = \frac{1}{2}, \quad \forall i.$$ 

The example demonstrates how the objective function is affected when the stopover duration of initially 10 hours is incrementally cropped. This corresponds to increasing the standard deviation of the prediction.

In this example the crop is done by removing the first and last elements of every parameter in the optimization model, see equation 2. This can be different from actual events since the standard deviation of last plugin prediction may be different from that of first plugout prediction. The result shows the intuitive result that if the stopover duration decreases then the cost of charging is more.

A more thorough sensitivity analysis could be carried out on the parameters and these should at least include charging intervals, price time series and energy targets. Since data describing the energy targets was not available to the authors at the time of writing this has not considered.

### VIII. FURTHER EXTENSIONS OF THE MODEL

An interesting possibility is to let the EDISON EV aggregator target the ancillary services (A/S) markets. A/S markets in general reward the capability of fast response which nicely matches the capabilities of an aggregated group of EVs. In Denmark, markets such as 'Secondary reserve' and 'Frequency controlled normal operation reserve' are valid candidates for EV participation, potentially offering a higher economic incentive than the earnings gained through smart charging alone. A future paper could seek to demonstrate how smart charging and A/S can be combined by the aggregator to maximize the overall economic value of controlled charging while still adhering to all the constraints and considerations listed in this paper.

### IX. ADDITIONAL OPTIMIZATION CONSIDERATIONS

Although the optimization methods presented in this paper primarily seeks to reduce the cost of energy, there are a great many additional parameters to be considered in the charging of an EV. The primary sources of such considerations are the distribution grid that connects the EV to the power system, the driving demands of the user of the EV and the internal battery pack of the vehicle. The following will attempt to list the most important of these considerations.

#### A. Distribution grid constraints

Analyses of the impact of EVs on the power system have revealed that without intervention, EV charging will place substantial pressure on the grid, particularly at the medium and low voltage levels [1], [2], [3], [4]. The degree of grid congestion is dependent on a number of factors including local grid topology, penetration and distribution of EVs, and charging management procedures [5]. Congestion will lead to reduced asset life expectancies, and in turn increased network maintenance costs. Many studies have found that coordinated charging of vehicles is effective at reducing congestion, thereby increasing the penetration of EVs tolerable on any given network, and facilitating the deferral of grid reinforcement [1], [4].

Numerous approaches to dividing and managing available grid capacity are proposed within the literature. These can be generally summarized as follows:

| Static capacity allocation | Where each EV or aggregator has a fixed portion of the capacity allocated to them, i.e. a certain maximum allowed load in watts pr node. This approach is relatively easy to implement but will not efficiently use the available grid capacity. |
| Grid capacity market | Where a dynamic market is implemented in which the EVs, or the aggregators representing them, would bid for certain amounts of the available capacity. |
| Dynamic tariff price signals | Aggregators or individual EVs respond to a price signal that is representative of the congestion at each node, and optimize their charging schedule accordingly. |
Regardless of which of the above methods is used, an aggregator or fleet operator represents an efficient approach to coordinate EV charging to avoid grid overload. In [10] a ‘Plug-In Hybrid Electric Vehicle (PHEV) manager’ is used to coordinate all EV charging within a given zone, where the manager is aware of the grid capacity and can optimize charging with respect to this. Alternatively, [9] proposes an iterative approach where each aggregator coordinates the charging of their fleet and reports this to the DSO.

A way to include grid considerations in the optimization defined in this paper is to limit the range of available charging powers at certain points in time.

If there is a need for incorporating grid constraints in model 2 it may be useful to let \( p \in \mathbb{R}^{n \times m} \). Every row \( p \) is then the possible charging configurations at time \( j \) where \( j = 1, \ldots, m \).

B. Battery constraints

Another important area of research is on the lifetime of EV batteries and the factors that influence it. Francesco et al. [18] has defined the following formula which summarizes the major factors that has an influence on the battery lifetime \( L \).

\[
L = f(c_r, T, D, c_d),
\]

where \( c_r \) is the charging cycles, \( T \) the temperature, \( D \) the depth of discharge and \( c_d \) the charging rate. For most, if not all EVs, some sort of Battery Management System (BMS) will monitor and to some degree control the above parameters as to maximize the battery lifetime. One parameter relevant to the aggregator is the charging rate. For lithium Ion batteries, the charging power should be reduced when the SOC exceeds a certain percentage. If this is not considered in the definition of the algorithm, less energy might be available at the beginning of a trip than defined by the energy target of the charging schedule. One solution is simply to ignore the last roughly ten percent of the available energy capacity when generating a charging schedule.

C. EV owner driving requirements

Driving predictions should be a tool to simplify the EV owner’s management and control of smart charging. It should, however, always be possible for the EV user to assume direct control of the charging process. The main parameters that the EV user must be able to set are the energy demand and starting time of the next desired trip. If such parameters are explicitly defined by the user they will overwrite the values calculated by the prediction algorithm. EV owner requirements can be met by the optimization algorithm by simply setting the energy target \( E \) and start time of the next trip to values defined by the user.

At times, the EV owner might even wish to overwrite smart charging all together, by choosing to instantaneously start charging at the highest possible charging power. This would disable any kind of optimization.

X. Conclusion

This paper has presented the mathematical methods used by the EV aggregator software developed in the EDISON project. It has been demonstrated how a set of driving data from combustion engine vehicles in the Copenhagen area has been used by a model to predict nightly stopovers. All of the predicted stopover intervals lie in the 95% probability region (see figure 6). Considering the lower bound of the prediction interval yields that 6.7% could lie outside the 95% probability region (figure 7).

The prediction model is used by a suggested optimization model to minimize charging costs based on hourly spot market energy prices. It has been illustrated how the predictability of the data, measured on the standard deviation, will influence the result of the objective function (figure 8).

Various additional parameters and constraints relating to the grid, the EV owner and the EV battery have been discussed for the sake of completeness, and it has been indicated how some of these considerations can be added to the optimization model.

Finally, ideas regarding further developments have been mentioned. This includes adding revenue from acting on ancillary service markets to the savings earned by smart charging.

Figure 9 shows a screenshot from the aggregator software interface. The screenshot includes three graphs that shows a charging schedule (bottom), the energy prices (middle) and the predicted vs. measured availability (top) over a 24 hour period for a single simulated EV.

Fig. 9. Screenshot/EDISON EV aggregator.

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9. CORE PUBLICATIONS

F  Facilitating a Generic Communication Interface to Distributed Energy Resources - Mapping IEC 61850 to RESTful Services

This paper was published in the Proceedings of the First IEEE International Conference on Smart Grid Communications (SmartGridComm), 2010, Gaithersburg, MD, USA.
Facilitating a Generic Communication Interface to Distributed Energy Resources
Mapping IEC 61850 to RESTful Services

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Abstract—As the power system evolves into a smarter and more flexible state, so must the communication technologies that support it. A key requirement for facilitating the distributed production of future grids is that communication and information are standardized to ensure interoperability. The IEC 61850 standard, which was originally aimed at substation automation, has been expanded to cover the monitoring and control of Distributed Energy Resources (DERs). By having a consistent and well-defined data model the standard enables a DER aggregator, such as a Virtual Power Plant (VPP), in communicating with a broad array of DERs. If the data model of IEC 61850 is combined with a set of contemporary web protocols, it can result in a major shift in how DERs can be accessed and coordinated. This paper describes how IEC 61850 can benefit from the REpresentational State Transfer (REST) service concept and how a server using these technologies can be used to interface with DERs as diverse as Electric Vehicles (EVs) and micro Combined Heat and Power (µCHP) units.

I. INTRODUCTION

Several standards are currently under development that can facilitate communication with DERs in a smart grid constellation. Among these are OpenARD [1], OpenAMD [2] and EMIX [3] as well as the IEC 61850 standard, on which this paper will focus. The standard is thoroughly researched and has been described in several papers [4] [5]. The standard offers a structural decomposition of the units to which it communicates. This means that each subcomponent of a DER can be described by the information model of IEC 61850. This makes the standard suitable for scenarios in which an aggregator needs a fine-grained knowledge and control of the state, structure and operation of a DER. The standard is a good match for the virtual power plant concept, in which an intermediate entity represents an aggregated group of DERs in the power system and on the market. Apart from the syntactic level, the standard also defines the protocols that carry the data over a network. Without providing any recommendations on the medium used, the standard proposes the use of the TCP/IP protocols to enable internet communication. On the upper part of the ISO OSI stack, the standard describes the use of the Manufacturing Message Specification (MMS) standard as an application-level protocol [6]. Replacing MMS with REST services will, however, have certain advantages. A REST service is a special flavor of web services which are connected to the concept of a Service Oriented Architecture (SOA). As REST services represent both a simple and well- documented concept for achieving a high degree of interoperability, they are a good candidate for use in the IEC 61850 protocol stack. The next chapter describes IEC 61850 and REST in greater detail. Then, the paper describes how an IEC 61850 server was developed based on the above technologies, and finally a case is defined for interfacing with a µCHP unit and an electric vehicle. The IEC 61850 via REST implementation suggested in this paper is used in the Danish EDISON project [7], where a VPP-like aggregator should coordinate the charging of electric vehicles, as well as in the Danish Generic Virtual Power Plant project, where µCHPs are coordinated to support the grid.

II. THE IEC 61850 STANDARD

The IEC-61850 standard was designed to enable interoperability between different devices in the substation environment, and to facilitate the adaptation of future networking technologies. One of the cornerstones of the standard is a layered data model (see Figure 1), which has been designed to closely model the physical substation environment.

A. Data model

The logical device is a virtual representation of a physical device within the substation. It is comprised of a name, a path to the object itself and a list of logical nodes. A logical device contains one or more logical nodes, which represent various components in the physical device.

As an example, the setup tested contains a logical node called MMXN. The MMXN part of the name refers to the type of the node, which in this case is “Non-phase-related measurements” [8]. Apart from the name, the MMXN class must also contain all the data classes defined by the Logical Node Class defined by the standard [8]. Beside this, instances of the MMXN class can include a list of optional data classes and attributes. The data classes represent meaningful information inside the nodes and are declared recursively.
An attribute can either be a simple type, such as FLOAT32, INT24 or BOOLEAN, or it can consist of both other simple and complex attributes.

B. Data-Sets
The logical nodes can contain data-sets, which contain sets of data that have a natural association [10]. Data-sets are primarily used for reporting and logging [10], but can also be requested directly. Included in the data-sets are properties stating when a report/log should be triggered. An example of a triggering condition is “Data Change”.

C. Logging and reporting
The IEC 61850 outlines a reporting mechanism, which is essentially a payload-carrying event that is sent back to the subscribing clients when triggered. Reporting is directly linked to data-sets as it is the data attributes in the data-sets that specify the trigger conditions. Closely related to reporting is logging. They both rely on the data-sets for triggering, but the reports are sent back to the clients, whereas the logs are persisted locally [10].

D. Object references
Any object within the data model can be referred to directly via its object path [10]. Because of the tree-like properties of the model, this path resembles a fully-qualified file-name notation. The path lists all the objects on the route from the root of the model to the object in question. Where fully-qualified file-name notation usually has a fixed delimiter between object names, the IEC-61850 references use a slash to separate the logical device from the rest of the path, which is then separated by periods.

Included in the object reference is a filtering mechanism called functional constraints (FC), which is used to group the data-attributes. The functional constraints are usually specified at the end of an object reference, incased in square brackets. For the DC example, this would result in the path:

CHP1/MMXN1.Watt.mag.[‘DC’]

Because the paths resemble a fully-qualified file-name notation, they can easily be mapped to a URL, which makes the data model near perfect for REST. As the physical device and the server are not referred in the object path, a REST URL could look something like:

http://hostname/device/node/class/attribute

Included in IEC 61850 is also a service specification called the Abstract Communication Service Interface (ACSI) [11], which outlines a set of methods that are used when communicating with the system. These methods have been mapped to REST.

III. REST SERVICES
The REST architectural style was first described in 2000 in a Ph.D. dissertation by Roy Fielding [12]. The industry did, however, not embrace REST right away, probably because at about the same time, the Single Object Access Protocol (SOAP) [13] was embraced by most of the large software vendors and therefore got a lot of attention. As time passed and SOAP grew, adding numerous extensions, people started looking for a lighter, more web-centric alternative. Today many big web companies provide REST services for others to interact with their systems. These include companies such as Amazon, Google, Yahoo and Facebook.

Where SOAP comes complete with a seemingly ever-growing suite of extensions, the primary aim of REST is to stick closer to the basic functionality of the HTTP protocol on which the web is based. Unlike SOAP, there is no standard available that describes REST. Instead, developers should follow the REST principles when creating a RESTful [14] service.

The most important REST principle is to expose the resources in a RESTful service as unique URLs. An example of this might be a library service where the whole book catalog could be accessed by using the URL http://library.com/books/ whereas a single book could be accessed using the URL http://library.com/books/123 (where
123 is the ID of the book). As opposed to SOAP services, where you would issue a method call such as createBook, deleteBook, RESTful services utilize the HTTP methods, GET, POST, PUT and DELETE for reading, creating, updating and deleting resources, respectively.

The REST principles do not define any specific format for request or response data. Most common, however, is the XML format, but other formats such as JavaScript Object Notation (JSON) [15] are becoming increasingly popular, especially in Asynchronous JavaScript And XML (AJAX) services. Ideally the client is able to ask for specific representation by setting the Accept request header to the desired format name.

Like the HTTP protocol itself, RESTful services are stateless, meaning that no state should be stored on the server between requests from the client. Each request should therefore contain all the information necessary to serve the client. RESTful services also embrace other aspects of the HTTP protocol, such as status codes, conditional get and caching.

Status codes are sent along with any HTTP response and indicate the type of the response. Examples of common status codes are 200 (OK) for a successful request and 404 (NOT FOUND) for a request for a non-existing resource. HTTP defines status codes in the range 1xx to 5xx.

Conditional Get allows the client to ask the server whether the requested resource has changed since it was last retrieved. This is achieved either by sending the If-Modified-Since header with its value set to the time of the last retrieval or by sending the eTag header that came with the last response. If the resource has not been modified the server only returns status code 304 (NOT MODIFIED). This can be important for performance, as unchanged data does not need to be re-sent.

Another closely related header is the cache header, sent along with the response from the server. The cache header allows the server to tell the client whether and for how long the client should cache the response. This improves performance as it saves the client from requesting the same data again, if it is not expected to change. This is mainly used for static resources, such as images on the web, but can also be utilized in RESTful services.

The functionality of RESTful services is very closely related to the functionality of the web, which has been extremely successful over the last couple of decades. This is mainly due to its scalability, interoperability and the fact that it is simple and easy to understand. HTTP and the WWW are used for a wide variety of tasks ranging from personal home pages to secure internet-banking and e-commerce. HTTP already has a built-in authentication mechanism but since many, if not all of the tasks mentioned call for strict security, several protocols have developed to add things like encryption to HTTP. Among some of the more well-known ones are open standards, such as the TSL/SSL [16] protocols. Because of technologies like these and the needs from which they arose, the idea of using REST for communication in electrical systems, as is the case with the VPP and the distributed energy resources, could surely be considered safe.

IV. RESTFUL INTERFACE FOR IEC 61850

As mentioned, the IEC 61850 reference paths resemble a fully-qualified file-name notation or a URL. This simplifies the task of creating a RESTful interface for the IEC 61850 data model. The idea is that the various objects in the data model hierarchy can be thought of as resources, which can be accessed by using the IEC 61850 object reference. As an example the data attribute

CHP1/MMXN1.Watt.mag.f

belonging to logical device “CHP1”, logical node “MMXN1” and so on would have the URL

CHP1/MMXN1/Watt/mag/f

and the entire “Watt” data object could be retrieved with the URL CHP1/MMXN1/Watt. For getting data, as in the example above, an HTTP GET request would be used. The server would then respond with the requested data in XML format as shown in Figure 3. For setting data, the same URL would be used, but with the HTTP method POST instead of GET.

![Figure 3 - REST communication overview.](image)

The ACSI interface described in IEC 61850-7-2 enables clients to inspect the data model, to read and write data, and to access data-sets, logs and more. To do so, the client calls methods such as GetDataValues and SetDataValues. These methods resemble traditional methods in a programming language with input arguments and return values. As described above, the REST architecture guidelines define services as a set of resources instead of methods as in the case of ACSI.

To make a resource-oriented interface for the IEC 61850 standard, a mapping from the ACSI methods to URL and HTTP method-pairs has been defined. The mapping for the data model of the IEC 61850 standard is shown in Table 1.

<table>
<thead>
<tr>
<th>Mapping</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GET</td>
<td>GetDataValues</td>
</tr>
<tr>
<td>POST</td>
<td>SetDataValues</td>
</tr>
</tbody>
</table>

Mappings for data-sets, reporting, logging, setting-groups and substitutions can be made in a similar manner. These mappings are presented in full detail in [9].

The first column in Table 1 shows the URL template of a resource, the second column shows the HTTP method used to get or set the URL, and the third column shows the ACSI services this resource replaces. The response from the GET requests to the resources shown in Listing 1 can be modified by using query string parameters. Three query string parameters have been defined: expandLevel, fc and includeValues.

The expandLevel parameter controls how big a portion of the data model is retrieved. The default value of this parameter is zero, which results in only the requested level of the data.
model being retrieved, as can be seen in Listing 1. Setting the `expandLevel` parameter to a higher number or to the value “all”, allows the client to retrieve bigger portions of the data-model hierarchy, as seen in Listing 2. By retrieving the whole data model, the client can easily inspect an entire logical device and a single URL can therefore replace multiple ACSI services.

The two remaining parameters accepted by the RESTful service are `fc` and `includeValues`. The `fc` parameter is used for filtering the data-model hierarchy to include only data attributes with the specified functional constraint. The `includeValues` parameter specifies whether the data values should be included in the response in addition to the data model.

The resulting output are the hierarchical IE 61850 data model in a concise and readable format. To show this, two URLs and their resulting output are given. Listing 1 shows a response containing a single value; Listing 2 is an example of what a larger view of the data model might look like.

### Table 1 - ACSI TO REST MAPPING

<table>
<thead>
<tr>
<th>URL</th>
<th>Method</th>
<th>ACSI equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>/</td>
<td>GET</td>
<td>GetServerDirectory (GetAllDataValues) (GetDataValues)</td>
</tr>
<tr>
<td>/[LD]/</td>
<td>GET</td>
<td>GetLDDirectory (GetAllDataValues) (GetDataValues)</td>
</tr>
<tr>
<td>/[LD]/[LN]</td>
<td>GET</td>
<td>GetLNDirectory (GetAllDataValues) (GetDataValues)</td>
</tr>
<tr>
<td>/[LD]/[LN]/[DO]</td>
<td>GET</td>
<td>GetDataDirectory GetDataDefinition (GetAllDataValues) (GetDataValues)</td>
</tr>
<tr>
<td>/[LD]/[LN]/[DO]/[DA]</td>
<td>GET</td>
<td>(GetAllDataValues) (GetDataValues)</td>
</tr>
<tr>
<td>/[LD]/[LN]/[DO]/[DA]</td>
<td>POST</td>
<td>SetDataValues</td>
</tr>
</tbody>
</table>

As Figure 3 illustrates, the response format of the RESTful service is in XML. Because of XMLs ability to model arbitrary data structures it is possible to represent the hierarchical IEC 61850 data model in a concise and readable format.

To show this, two URLs and their resulting output are given. Listing 1 shows a response containing a single value; Listing 2 is an example of what a larger view of the data model might look like.

1. `<DO Name="MaxRtDchPwr" Type="ASG" Ref="EV1/ZCEV1/MaxRtDchPwr">16800</DO>
2. `<DA FC="SP" Name="setMag" Type="Struct" Ref="EV1/ZCEV1/MaxRtDchPwr/setMag">`
3. `<DA Name="f" Type="FLOAT32" Ref="EV1/ZCEV1/MaxRtDchPwr/setMag/f">16800</DA>`
4. `</DA>`

As seen in Listing 2, a request for an entire data hierarchy can be quite verbose and might not be suitable for frequent use in a production environment. This kind of request is, however, very useful during the configuration and development phase when new devices need to be discovered. As the RESTful interface uses standard HTTP GET request, it is even possible to use a web browser to discover an IEC-61850-enabled device. As with ACSI methods such as `GetServerDirectory` and `GetLDDirectory`, the RESTful interface also enables clients to programmatically discover devices in a generic manner.

Although XML has been chosen as the output format in the example above, the RESTful interface could just as well use other output formats. Thanks to the Accept header discussed above, the same RESTful service could both accept and output XML and JSON. One argument for using the JSON format is that it is designed for serializing common objects, lists and scalar values found in virtually all programming languages and can therefore easily be deserialized by those languages. And without the verbose declarations, it is definitely more compact. JSON libraries exist for all major programming languages/frameworks, including Java, .Net, C++, Python etc [17].

As discussed in Section II, the IEC 61850 standard defines a reporting mechanism. Because of the connection-less nature of HTTP, and thereby of REST, implementing reporting callbacks to the client is not entirely straightforward. However, such mechanisms exist, for example the WebHooks model [18] proposed by Jeff Lindsay, NASA Ames Research Center. The approach is to have the IEC 61850 server enable clients to subscribe to reporting events, similar to the approach described in IEC 61400-25-3 [19], and pass along with that subscription request a callback URL which the IEC server can use for sending reports to the client as HTTP POST requests. Security must be kept in mind using this approach, because the client must be able to validate that the callbacks received did indeed come from the server. This could be solved using HTTP-based authentication or X.509 client certificates [20].

### V. CASE STUDIES

To test the usefulness of REST for mapping to the IEC 61850 standard, a server complying with both of these has been implemented. The server was designed “from scratch” to support multiple devices and to test the scalability of the REST implementation. The server has been written entirely in C# for the .NET framework.

To facilitate the deployment to embedded devices and add support for non-Windows systems, a small open-source in-process web server was chosen to host the REST interface. Except for the logging and reporting mechanisms, which run in the background, the server waits for requests from potential clients. When a request is received for a given URL, the server
looks up the requested object in its internal representation of the data
model. If the request is a “write” the server will simply return a status code as confirmation. In the case of a
“read”, however, the requested object is serialized to XML and returned to the client. One of the benefits of this approach
is that it is relatively simple to return not just the requested object but the entire sub-model. In fact, if a request is received
for the logical device the server is able to return the entire data model, including all the values, using a single response.

The goal of these case studies is to test the REST mapping
against different DERs, namely,

- to describe the µCHP setup and briefly show how the
communication has been mapped
- to touch upon the challenges of mapping the electric
vehicles and what was needed to accomplish this.

A. Case study: Interfacing with a µCHP

The server was designed using a modular plug-in architecture
with a generic interface, which enables easier adaptation and
installation of virtually any type of device.

Among the IEC-61850-enabled devices is a pair of Dachs
µCHP units from Senertec. The Dachs accepts a series of
different commands over the RS232 line and each of these
commands returns a different set of values. These values
include electrical and temperature measurements. When a
complex REST request is received, i.e., more than one data
attribute is requested, the IEC 61850 server requests each
required value from the Dachs module. The Dachs module
then locates the requested value in the set of values returned
by each of its commands. As the values are requested from the
Dachs module one at a time, the module caches the result of
each command for a fraction of a second to avoid having to
issue a command multiple times for each REST request.

B. Case study: Interfacing with an EV

Another example of a plug-in made for the server is for an
EV charging-spot. As no real vehicles were available at the
time of development, the plug-in was mapped to an EV
simulation instead, which further illustrates the versatility of
the system. The simulation includes both a charging-spot and
an EV, which contains a simulated battery. When the EV is
plugged into the charging spot an EV aggregator-server can
tell the charging spot to control the charging using schedules
sent via the IEC 61850 REST interface. Such an EV
aggregator-server is used in the EDISON project [21].

Two client applications were developed to demonstrate the
system and to facilitate testing. One of these demo
applications is a web client showing the various devices
attached to the server, as well as all the measurements
and controls available. A screenshot from the client showing one
of the µCHPs can be seen in Figure 5.

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**Figure 4 - µCHP module RS232 communication.**

**Figure 5 - Screenshot of the web client.**

**Figure 6 - Setup showing simulated EV and charging-spot.**

The charging spot therefore acts as a proxy for the EV. This
is in accordance to [9] and [21] and means that the EV does
not need a wireless connection for being utilized by the
aggregator server. Because of this, even though the charging
spot and the vehicle are simulated as individual entities, they
are mapped with the charging spot as the logical device and
the currently connected EV represented as a logical node. The
aggregator server, or any other client, can read various values
from the charging-spot and the EV via the IEC 61850
interface, such as the current power usage, the phases in use
and the current state of charge.
There is an addition to the IEC 61850 standard, the IEC 61850-7-420 [22], that deals specifically with DERs. After having analyzed the requirements for the charging spot and EV, it became apparent that this standard needed further extension. Logical nodes for charging-spots (ZCHS) and for EVs (ZCEV) have been defined. These nodes contain essential attributes such as the state-of-charge of the EV, power limits and battery capacity. For controlling charging and discharging of the EV, the logical nodes for energy schedule, defined in [22], have been utilized. Since these extensions are outside the scope of this paper and subject for a later publication they will not be further described here.

Figure 7 - Demo showing the current state of an EV.

Together with the EV simulation, a small graphical client was developed to show the current state of the EV and the charging spot. This application, which is shown in Figure 7, displays a small car that moves between the road and the buildings, representing one of the three possible states “in use”, “idle” and “plugged-in”.

C. Case study conclusion

Although μCHPs and EVs differ significantly in both function and composition, the cases presented in this section show how IEC 61850 with the REST interface can support communication with both types of DERs. The units can be monitored and controlled to optimize their behavior in relation to energy prices, user requirements and the state of the power system.

VI. CONCLUSION

The main aim of this paper has been to demonstrate how RESTful services, in conjunction with the data model of IEC 61850, can be used to increase interoperability and simplicity in DER communication. The IEC 61850 standard has a large and well-defined set of logical notes describing the various components and values of a DER unit. This paper has shown that the object reference path of the IEC 61850 data model can easily be mapped to the URL format in the resource-oriented approach used by REST. Besides offering an intuitive way of accessing information, REST also provides better interoperability and simplicity by shedding much of the complexity present in SOAP-based web services. The advantages of using IEC 61850 with REST have been demonstrated by building an IEC 61850 server and describing its functionality in two case studies.

There is no doubt that the ambition of actively integrating DERs into a smart grid constellation will rely on the utilization of contemporary web concepts and standards. This paper serves as an input to the identification of the ICTs capable of satisfying the communication requirements for the power system of the future.

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