Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
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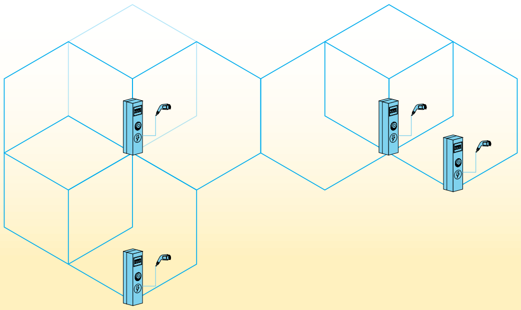
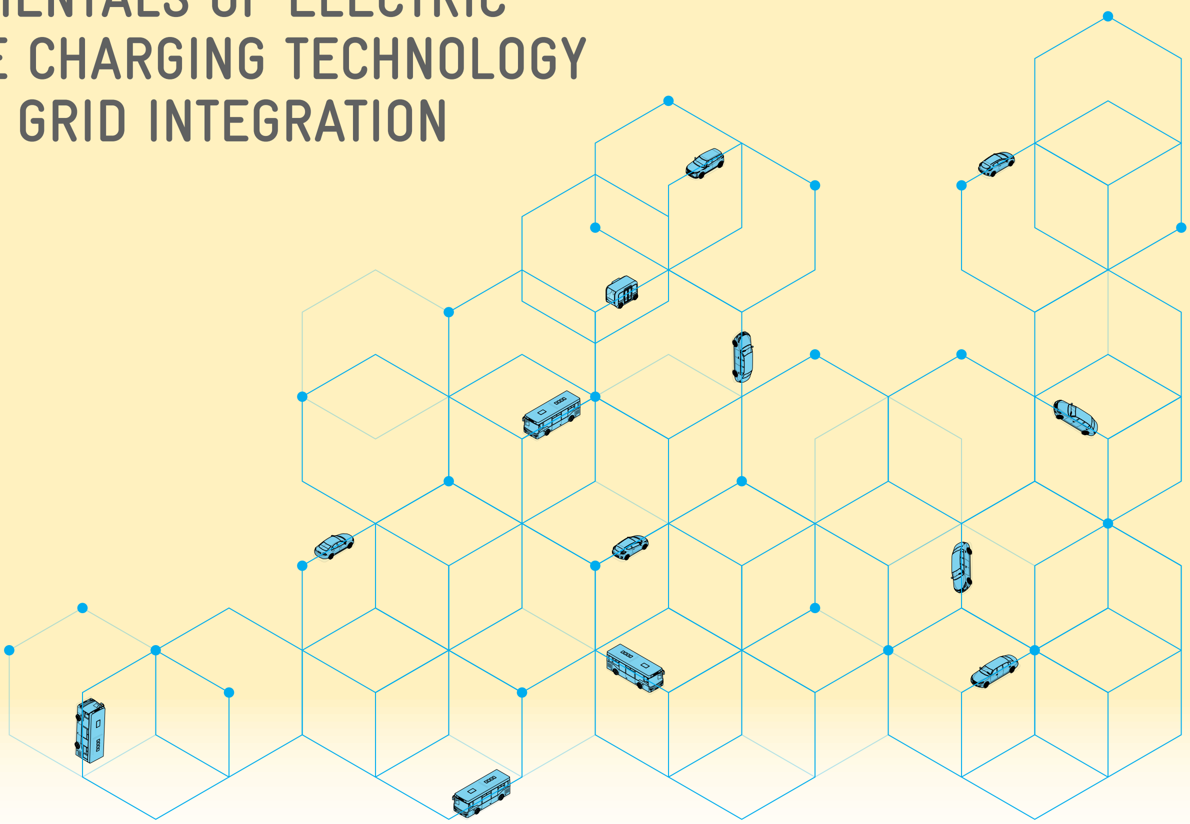
In cooperation with
NITI Aayog



INTEGRATION OF ELECTRIC VEHICLES CHARGING INFRASTRUCTURE WITH DISTRIBUTION GRID: GLOBAL REVIEW, INDIA'S GAP ANALYSES AND WAY FORWARD

REPORT 1

FUNDAMENTALS OF ELECTRIC VEHICLE CHARGING TECHNOLOGY AND ITS GRID INTEGRATION



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REPORT 1

FUNDAMENTALS OF ELECTRIC VEHICLE CHARGING TECHNOLOGY AND ITS GRID INTEGRATION

Acknowledgement

This publication has been prepared by Indian Institute of Technology Bombay (IIT Bombay) in collaboration with Florence School of Regulations Global (FSR Global), as a part of the Nationally Determined Contributions - Transport Initiative for Asia (NDC-TIA) initiative. NDC-TIA is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ and funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under its International Climate Initiative (IKI).

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FOREWORD

With the second-largest road network in the world, India's road transport contributes towards nearly 64% of the country's overall goods movement and caters to around 90% of India's total passenger traffic. This provides a huge opportunity to decarbonize the transport sector but there are also challenges. Government of India has taken proactive measures towards fostering a clean, connected, shared and cutting-edge transportation system by providing policy and regulatory support.

As India embarks on this ambitious journey towards sustainable mobility, a robust charging infrastructure will play a pivotal role. It must be understood that sector coupling between the energy and transport sectors is vital for e-mobility. With the growing number of EVs, the need for development of large network of charging infrastructure will only increase in the future. To support deployment of charging infrastructure in the country, the Government of India has allocated a total fund of INR 1000 Crore under the FAME II scheme. Under public procurement, Department of Heavy Industry (DHI) has sanctioned 2,636 EV Charging Stations, in 62 cities across 24 States/UTs and 1,544 such stations on highways under FAME II scheme. EV charging is a delicensed activity in India and the Ministry of Power (MoP) has published revised guidelines for Charging infrastructure for Electric Vehicles to facilitate the deployment of charging infrastructure. Apart from this, several states have announced targets for EV deployment including special EV tariff to incentivize EV charging in India. For the uptake of EV adoption in India, a major challenge of integrating the charging infrastructure with the electrical network needs to be tackled. The continued development of EV charging infrastructure and its integration will depend, among other things, on policy and regulatory environment, which must also account for grid stability.

I am glad to know that the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) has initiated a study focused on EV charging infrastructure, related policy and regulatory measures, grid integration of EVs, critical international review from eight countries, and way forward for smooth integration of EV charging infrastructure with the Indian grid.

I congratulate GIZ for the publication of this report.

(Amitabh Kant)

Place- New Delhi
Dated- July, 2021

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शुभाशिस् चौधुरी, निदेशक

FOREWORD

At the COP21 conference in Paris in 2015, India targeted to reduce its carbon footprint for every dollar of economic output by 33 to 35% within 2030 from what it was in 2005. The transportation sector being one of the largest consumers of oil and gas and emitters of greenhouse gases globally, need to be addressed on a priority basis. Fuelled by reducing manufacturing and component prices of equipment and improving the affordability of personal vehicles, India has seen a rise in on-road automobiles. Naturally, the transportation sector in India is one of the largest consumers of crude oil and a significant source of GHG emissions, even from an international standpoint. In 2013, the National Electric Mobility Mission Plan (NEMMP) 2020 was envisioned with a vision and roadmap for faster adoption of hybrid and electric vehicles and boosting indigenous manufacturing to achieve national fuel security and mitigate the adverse environmental impacts of road transport vehicles. Government of India further brought out the ambitious Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme to promote electric mobility in the country. The first phase of the scheme (FAME-I) began in 2015 and was extended till 2019, following which the second phase (FAME-2) began which has recently been extended till 2024. The initiatives being taken also have a broader plan to de-license the charging infrastructure business and mandate specific guidelines and standards for charging infrastructure for electric vehicles. This would further strengthen the market of public charging infrastructure and warrant a roadmap for the development of charging infrastructure. Although the Government has taken decisive steps towards faster adoption of EVs, several challenges and gaps are existing in the Indian EV ecosystem that needs to be addressed.

The Nationally Determined Contribution-Transport Initiative for Asia (NDC-TIA), a joint project of seven organisations, on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and with the engagement of China, India, and Vietnam is a welcome action. The project aims to promote a comprehensive strategy to decarbonising transport, i.e. a coherent system of effective policies coordinated among various sector ministries, civil society, and the private sector.

IIT Bombay is committed to playing a constructive role in achieving green and sustainable electrified transportation sector in the country. This specific study, "*Integration of Electric Vehicles Charging Infrastructure with Distribution Grid: Global review, India's Gap Analyses and Way Forward*", which is led by IIT Bombay, focuses on EV charging infrastructure, related policy and regulatory measures, grid integration of EVs, and the way forward for smooth EV adaption in the Indian EV ecosystem.

I would like to congratulate the authors, all the stakeholders involved, the reviewers, and the funding agencies contributing to the successful preparation of these reports.

(Subhasis Chaudhuri)

Date: 02.08.2021
Place: Mumbai

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Abbreviations

2 W	2 wheeler
3 W	3 wheeler
4 W	4 wheeler
AC	Alternating Current
ACE	Area Control Error
ADC	Analog to Digital Converter
ADR	Automated Demand Response
AENS	Average Energy Not Served
AGC	Automatic Generation Control
BEMS	Building Energy Management System
BEV	Battery Electric Vehicle
BMS	Battery Management System
CAIDI	Customer Average Interruption Duration Index
CAN	Controller Area Network
CCC	Controlled Current Charging
CCCV	Constant Current Constant Voltage
CCS	Combined Charging System
CHAdeMO	Charge de Move
CPCV	Constant Power Constant Voltage
CPO	Charge Point operator
CS	Charging Station
CSMS	Charging Station Management System
CVC	Controlled Voltage Charging
DC	Direct Current
DCFC	DC Fast Charging
DER	Distributed Energy Resource
DG	Distributed Generator
DISCOM	Distribution Company
DoD	Depth of Discharge
DoS	Denial of Service
DSO	Distribution System Operator
ECU	Electronic Control Units
EM	Electro Magnetic
EMC	Electro Magnetic Compatibility
EMI	Electromagnetic Interference
eMIP	E-mobility Interoperation Protocol
eMSP	electric Mobility Service Provider
ENS	Energy Not Served
EPBD	Energy Performance of Buildings Directive
EV	Electric Vehicle
EVCC	Electric Vehicle Communication Controller
EVCS	Electric Vehicle Charging Station
EVSE	Electric Vehicle Supply Equipment
FCEV	Fuel Cell Electric Vehicle
GENCO	Generation Company
HEV	Hybrid Electric Vehicle
HLC	High Level Communication
HMI	Human Machine Interface

ICCB	In-Cable Control Box
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineer
IGBT	Insulated Gate Bipolar Transistor
IoP	Interoperation Platform
IP	Internet Protocol
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standards
ITDD	Current Total Demand Distortion
LDO	Low-dropout regulator
LIN	Local Interconnected Networks
LoM	Loss of Mains
MBBL	Model Building Bye-Laws
MCU	Microcontroller Unit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOST	Media-Oriented Systems Transport
MPU	Micro Processing Unit
MSP	Mobility Service Provider
NDC-TIA	Nationally Determined Contributions-Transport Initiative for Asia
NTPC	National Thermal Power corporation
OCHP	Open Clearing House Protocol
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
OEMs	Original Equipment Manufacturers
OICP	Open Inter Charge Protocol
OLEV	online Electric Vehicle
OSCP	Open Smart Charging Protocol
PCS	Public Charging Station
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Carrier
PWM	Pulse Width Modulation
RFID	Radio Frequency Identification
RoCoF	Rate of Change of Frequency
SAE	Society of Automotive Engineers
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition System
SECC	Supply Equipment Communication Controller
SoC	State of Charge
SOP	Standard Operating Procedure
THD	Total Harmonic Distortion
TIR	Technical Information Report
ToU	Time of Use
TSO	Transmission System Operator
UNECE	United Nations Economic Commission for Europe
V2B	Vehicle to Building
V2G	Vehicle to Grid
V2H	Vehicle to Home
WAN	Wide Area Network
WPT	Wireless Power Transfer

Chapter 1: Introduction

The global Electric Vehicle (EV) fleet is poised to increase exponentially in what has been dubbed as the electric mobility revolution. The push for EVs is driven by the global climate agenda established under the Paris Agreement to reduce carbon emissions to limit global warming. Importantly, not only would a switch from combustion-engine vehicles to EVs lead to lower emissions, but it would also result in reduction of air pollution. In addition, the deployment of EVs is also driven by national agendas to reduce oil demand and as such dependence on oil imports, as well as the encouragement of a local EV manufacturing industry for job creation. On the other hand, through several grid support services, EVs are expected to strengthen the grid and help accommodate higher renewable energy penetration while maintaining secure and stable grid operation.

The global electric mobility revolution is today defined by the rapid growth in electric vehicle (EV) uptake. It is estimated that two in every hundred cars sold today are powered by electricity. This phenomenon is today defined by the rapid growth in EV uptake, with EV sales for the year 2019, reaching 2.1 million. The global EV fleet totalled 7.2 million in 2019 with EVs accounting for 1 % of the global vehicle stock and 2.6 % of global car sales.

In India, EVs currently represent a small share with approximately 750,000 vehicles. The country has set a target of 30% electric vehicle sales across all vehicle types by 2030. India has over 250 million vehicles, and this fleet is dominated by 2-wheelers, accounting for 78% of the total vehicles. Amongst the different vehicle segments, public buses, taxi fleets, 2-wheelers and three-wheelers are expected to be the first adopters of EVs. As the country is at an early stage of EV deployment, public charging infrastructure is still limited. In this context, the Ministry of Power has already identified 9 major cities and 11 intercity routes as pilots to enable EV charging infrastructure. Similarly, a number of states have also started introducing policies to promote EV adoption and charging infrastructure deployment, with Meghalaya being the latest state to introduce the draft EV policy (February 2021). Currently (as of February 2021) 15 states and Union territories of India have final or draft EV policies in place.

The rapid growth in EV uptake required to reach India’s policy targets will have to address two major challenges. The first challenge is ensuring the deployment of the charging infrastructure required to serve the needs of the ever-growing number of EVs. The second challenge is the secure and efficient integration of EVs into the power system The success of the EV revolution hinges primarily on the timely deployment of effective EV charging infrastructure. However, at the same time, EV adoption is the main driver for the business case of EV charging infrastructure. Policy and regulation, informed by a thorough understanding of the EV charging ecosystem, can offer solutions to this chicken-and-egg problem.

Although the e-mobility plan is developed at the central level, the onus is on the state governments, which have to develop and implement policies and regulatory frameworks to enable the adoption of EVs and deployment of charging infrastructure in their respective states. Thus, considering India's federal structure as well as the wide variance in the social-geographic and economic variances between states, a one-size fits all approach cannot be applied (an example being the use of informal form of transportation in varying social geographies). The development of adequate charging and power system infrastructure to support the up-take of EVs would rest upon state-specific policy, regulatory measures, and effective implementation of such policy and regulatory interventions.

1.1 About this Study

The Nationally Determined Contribution – Transport Initiative for Asia (NDC-TIA) is a regional initiative funded by the International Climate Initiative (IKI) of German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). It is a joint project of seven organizations and with the engagement of China, India, and Vietnam. The organizations partnering with GIZ on this project are World Resources Institute (WRI), International Council on Clean Transportation (ICCT), International Transport Forum (ITF), Agora Verkehrswende, REN21 and SLOCAT. For the India component of the NDC-TIA project, the implementing partner is the National Institution for Transforming India (NITI Aayog).

Under the NDC-TIA India Component, we have an ongoing project "Integration of Electric Vehicles charging infrastructure with distribution grid: Global review, India's gap analyses and way forward" which is focused on conducting Indian and International review on overall environment related to EV charging. This project is carried out by consortium led by IIT Bombay along with Florence School of Regulation (FSR), Technical University Denmark (DTU), Cardiff University and Universidad Pontificia Comillas.

This specific study focuses on EV charging infrastructure, related policy and regulatory measures, grid integration of EVs, and the way forward for smooth EV adaption in the Indian EV ecosystem. The study developed a framework along with the inputs from a detailed critical international review on EV charging infrastructure development and its grid integration from different EV rich countries. The developed framework has been used as a basis for *identifying gaps and scope for improvement* in EV charging infrastructure adoption at the national level and in the States. The study based on a combination of desk *research, surveys, bilateral consultations with stakeholders, and* consolation workshops has been used to identify and *recommend National and state specific interventions* that can be sandboxed for the use by regulators, policy makers, DISCOMS, and other stakeholders, and later adopted statewide.

1.1.1 Aim of the Study

The aim of this study is to conduct a high-quality study with high impact/quality reports that can be used by the Government of India including State Governments, distribution system operators, transmission system operators, planning and regulatory agencies and other stakeholders (EV industry etc.) to frame, adapt, and/or revise policies, regulations, technical charging standards, communication protocols related to the integration of EV charging infrastructure with distribution and the transmission grid.

1.1.2 Objectives of the Study

A detailed study was conducted based on critical international review on EV charging infrastructure and its grid integration from different EV rich international countries (besides India) with the main thrust on the following points:

- Planning and operation of the distribution grid with integration of EV charging infrastructure
- Grid support services from electric vehicles to facilitate large-scale renewable energy integration
- Technologies and standards for EV charging infrastructure's integration with distribution grid
- Policies and regulations for EV charging infrastructure and integration with distribution grid
- Identifying the key challenges and recommendations for efficient, effective and sustainable integration of EV charging infrastructure in India

1.1.3 Organisation of the Study Reports

The outcome of this study is documented in a series of four technical reports. The four reports listed below cover different aspects of EV integration in a structured manner for effective, organised, and easy dissemination of the study outcome.

- **Report-1: Fundamentals of Electric Vehicle Charging Technology and its Grid Integration**
- **Report-2: International review of Electric Vehicle Charging Infrastructure and its Grid Integration**
- **Report-3: Status Quo of Electric Vehicle Charging Infrastructure and Grid Integration in India**
- **Report-4: Gap analysis and Recommendations for EV integration in India**

Report-1: Fundamentals of Electric Vehicle Charging Technology and its Grid Integration

This specific report is the first in the series of four reports documenting the fundamentals of EV charging technology, standards, communication protocols, and grid integration of EVs with the distribution system. The functional role of EV charging in the EV ecosystem is discussed in detail.

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<tr><th>Basics of EV charging</th><th>Aspects of Interoperability</th><th>Challenges for Grid integration of EVs</th><th>Grid Support from EVs</th><th>Smart Charging & Cyber security</th></tr>
<tr><td rowspan="2">Charging Technologies</td><td rowspan="2">Communication Protocols</td><td>Voltage stability issues</td><td rowspan="2">Voltage Control</td><td rowspan="2">Basics of Smart charging</td></tr>
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<tr><td>Impact of Harmonics on Transformer life</td></tr>
</table>

1.2 Key Terminologies used in the EV Ecosystem.

- **Electric Vehicle (EV):** Any vehicle which has an electric motor and can be powered by battery storage, fuel cell, photovoltaic array, or any other source of electric current. An EV can either be a hybrid electric vehicle or a battery electric vehicle.

- **Battery Electric Vehicle (BEV):** A battery electric vehicle is only powered by a battery storage and cannot be powered by any other type of fuel.

- **Hybrid Electric Vehicle (HEV):** An HEV combines an internal combustion engine powered by conventional fuels with a battery-powered electric motor. The battery is charged using the IC engine and through regenerative braking.
- **Plug-in Hybrid Electric Vehicle (PHEV):** PHEVs are hybrid EVs, but the batteries in PHEV can be charged by plugging into an electrical outlet.
- **Charging Point/ Electric Vehicle Supply Equipment (EVSE):** A charging point or an EVSE is the actual point of connection of the EV with the electrical network. A charging point or EVSE can have different connectors attached to it for compatibility purposes but only one may be used at a time. (SWEEP, n.d.)
- **Charging Station/ Electric vehicle Charging Station (EVCS):** A charging station or EVCS is the physical station with one or more charging points.
- **Charging Pool:** A charging pool consists of multiple charging stations within a geographical area as shown in Figure 1.1. The charging pool is operated by one charge point operator.
- **Connector:** A connector is a physical interface between the EVSE and the EV. Based on different standards there are different connectors such as J1772, Mennekes Type 2 connector etc.
- **Charge Point Operator (CPO):** The charge point operator is responsible for the management, maintenance, and operation of the charging stations.

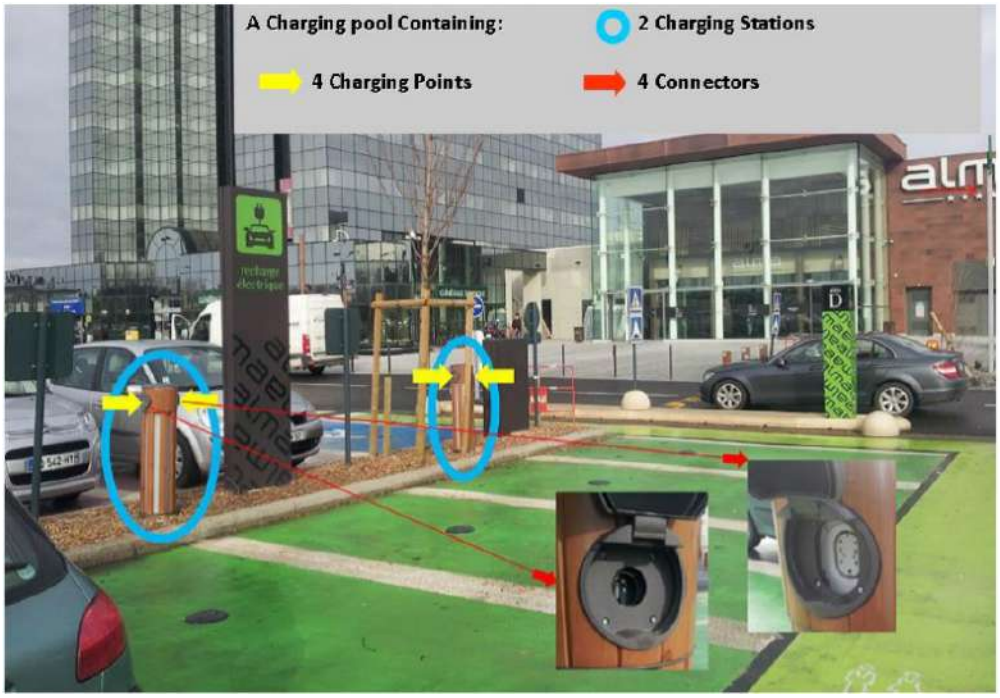


Figure 1.1: A charging pool with multiple charging stations and charging points (NEA, 2019)

1.3 Types of Electric vehicles

Classification of EVs can be done based on their chassis and engine type. The chassis includes 2-wheelers, 3-wheelers, 4-wheelers, trucks, buses, and mobile machinery. Furthermore, United Nations Economic Commission for Europe (UNECE) in 2017, categorises vehicles through the following categories,

- **Category 1**: a power-driven vehicle with four or more wheels designed and constructed primarily for the carriage of people with two sub-categories,
    - 1.1: less than eight seats
    - 1.2: More than eight seats.
- **Category 2**: a power-driven vehicle with four or more wheels designed and constructed primarily for the carriage of goods. This includes mobile machinery.
- **Category 3**: a power-driven vehicle with 2 or 3 wheels designed and constructed for the carriage of persons and/or goods.'
    - 3.1: 2 wheelers (2W) Moped,
    - 3.2: 3 wheelers (3W) Moped,
    - 3.3: 2W Motorcycle,

- 3.4: tricycle,
- 3.5: Motorcycle with sidecar.

The type of engine can be one of three categories (Lie et al., 2017):

a) **Hybrid EV (HEV)** - These combine a conventional internal combustion engine system with an electric propulsion system (examples include the Toyota Prius and Ford Escape Hybrid)

b) **Battery electric vehicle (BEV)** - These derive all power from battery packs and thus have no internal combustion engine, fuel cell, or fuel tank (examples include the Nissan Leaf and Tesla Model S)

c) **Fuel cell electric vehicle (FCEV)** - These convert chemical energy of a fuel (often hydrogen) into electricity (examples include the Honda Clarity).

1.4 Stakeholders in EV Ecosystem

The EV ecosystem includes a variety of stakeholders as shown in Figure 1.2, between whom proper coordination and communication is necessary for the growth of the EV market. These stakeholders include,

- **Original Equipment Manufacturers (OEM):** OEMs includes charger manufacturer, vehicle and its components manufacturer etc.
- **Charge Point Operator (CPO):** The charge point operator is responsible for the smooth operation of the charging station.
- **Electric Mobility Service Providers (eMSP):** The eMSP offers EV charging services to the EV users by providing access to the charge points within the eMSP network.
- **Energy Distributor/retailer**: They provide the energy to the CPOs for the charging needs.
- **DISCOM/DSO:** The electrical connection to the charging station is provided by the DISCOM and so the CPO needs to coordinate with the DSO regarding connection requirements as well have communication layers in place to control the charging load based on the network condition.
- **Public Authority:** The public authorities are responsible for framing policies to increase the growth of the EV market as well as frame regulations for grid integration of EV.
- **IT & Communication:** They provide communication services between the different associated stakeholders and provide cybersecurity services.

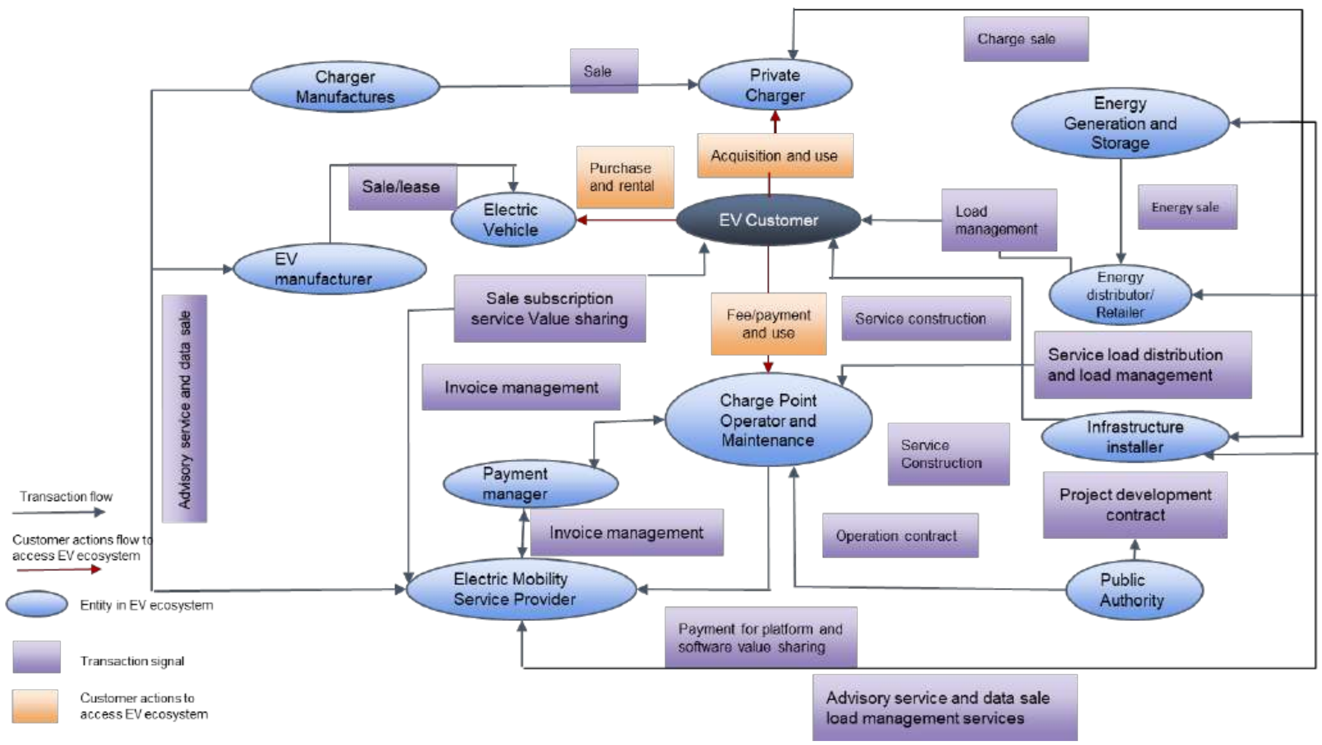


Figure 1.2: Diagrammatic representation of EV ecosystem, with few examples of relevant stakeholders

Before identifying the challenges and barriers for grid integration of EV charging infrastructure, it is imperative to understand the fundamentals of the technology involved. In this light, this report will comprehensively cover the technology behind EV chargers, relevant standards, protocols, communication, and grid related aspects.

Chapter 2: Charging technologies for Electric Vehicles

Electric vehicle chargers have evolved over the years and presently various types of chargers are available in the market to serve different categories of EVs. Electric vehicle charging can be classified into different types as shown in Figure 2.1. Based on the technology used for charging, it is classified into Conductive (plug-in), Wireless, and Battery swapping.

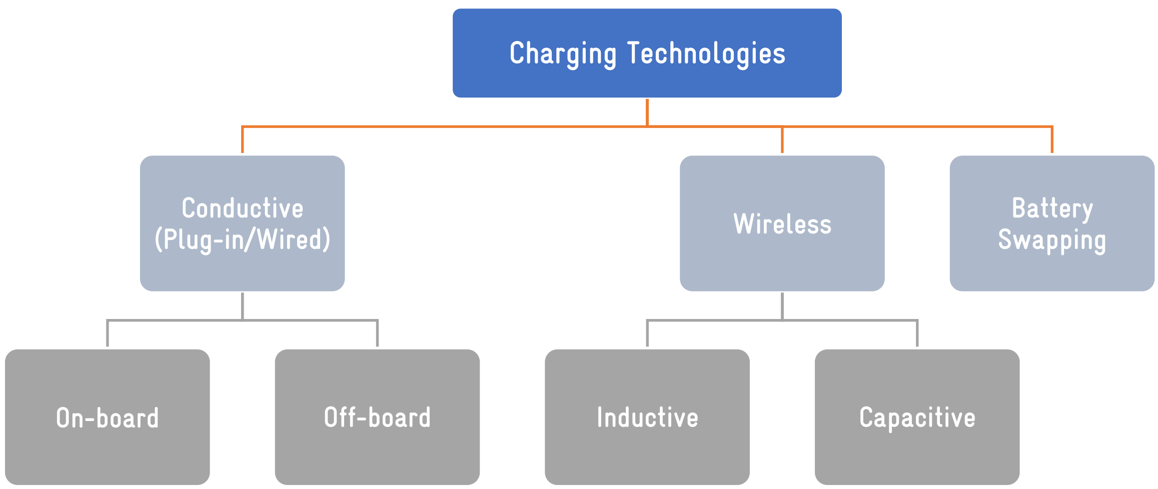


Figure 2.1: Classification of EV charging technologies

The charging infrastructure can be distinguished in terms of speed of charging, standardisation of chargers, ownership, process of charging and power flow directionality, as shown in Figure 2.2 This report builds on the analytical framework presented in (Bhagwat et al., 2019) to define EV charging infrastructure.

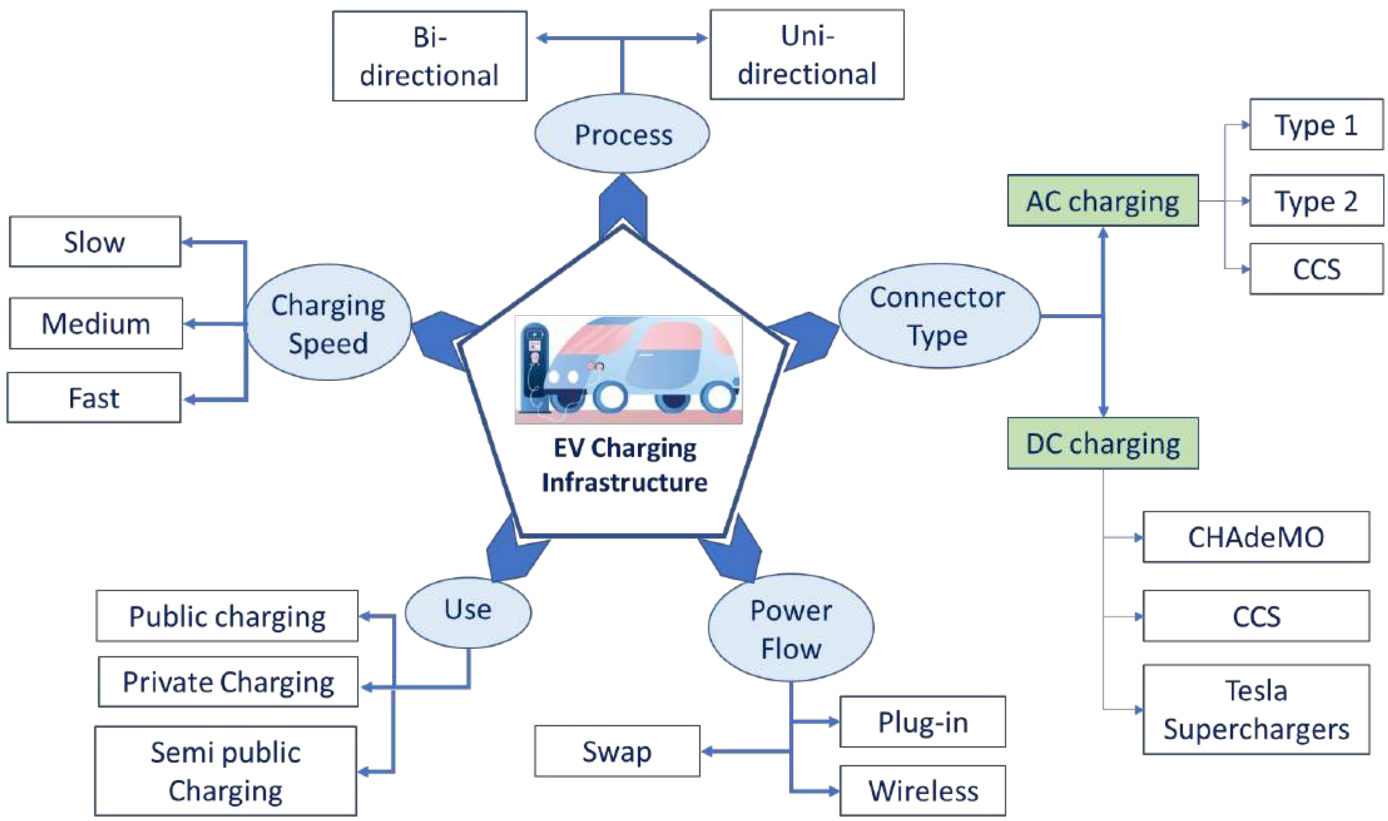


Figure 2.2: EV charging infrastructure classification

2.1 Conductive (Plug-in/Wired) charging:

The wired charging use either AC or DC power to charge the EV from EVSEs. The wired EV chargers can be either on-board or off-board, depending on whether the charger is in the EV or in the EVSE. In the case of on-board chargers, the AC power is supplied to the on-board converter, which then converts it to DC to feed it to the battery. This restricts the on-board charger's power rating due to the bulkiness of the converter and space constraint within the EV. So, they can charge the EV at a slow/moderate rate. However, in the off-board chargers, the converters are part of EVSE and directly supply the DC power to the EV battery bypassing the on-board charger and hence they can charge the battery at a faster rate. The overall schematic of conductive EV charging is shown in Figure 2.3.

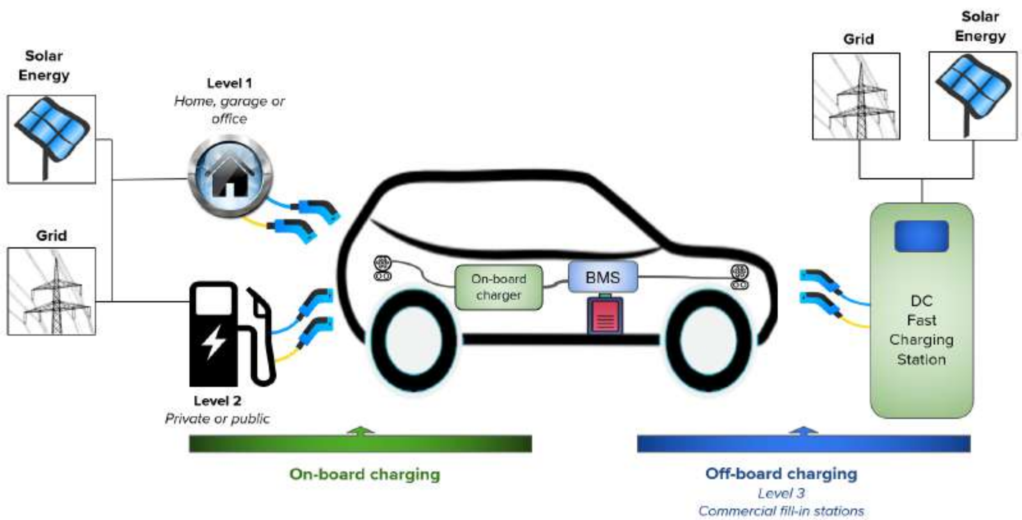


Figure 2.3: EV charging infrastructure

2.1.1 Modes of Charging

The IEC 61851 standard has defined different modes for EV charging:

- **Charging mode 1** uses regular 230 V, AC sockets. Mode 1 is limited to a maximum charging capacity of 2.3 kW to ensure safety as it lacks communication.
- **Charging mode 2** uses an In-Cable Control Box (ICCB) with a regular 230 V socket. The ICCB controls the charging capacity. Although normally used at 2.3 kW (1-phase, 10 A), Mode 2 has a maximum charging capacity of 7.4 kW (single phase, 32 A) or 22 kW (three-phase, 32 A).

- **Charging mode 3** determines the adequate charging capacity by communication between EV and charging point. Most mode 3 public charging points deliver 11 kW, 22kW or fast charging.
- **Charging mode 4** is DC charging and is usually applied for fast charging. Charging capacity ranges from 50 kW and higher.

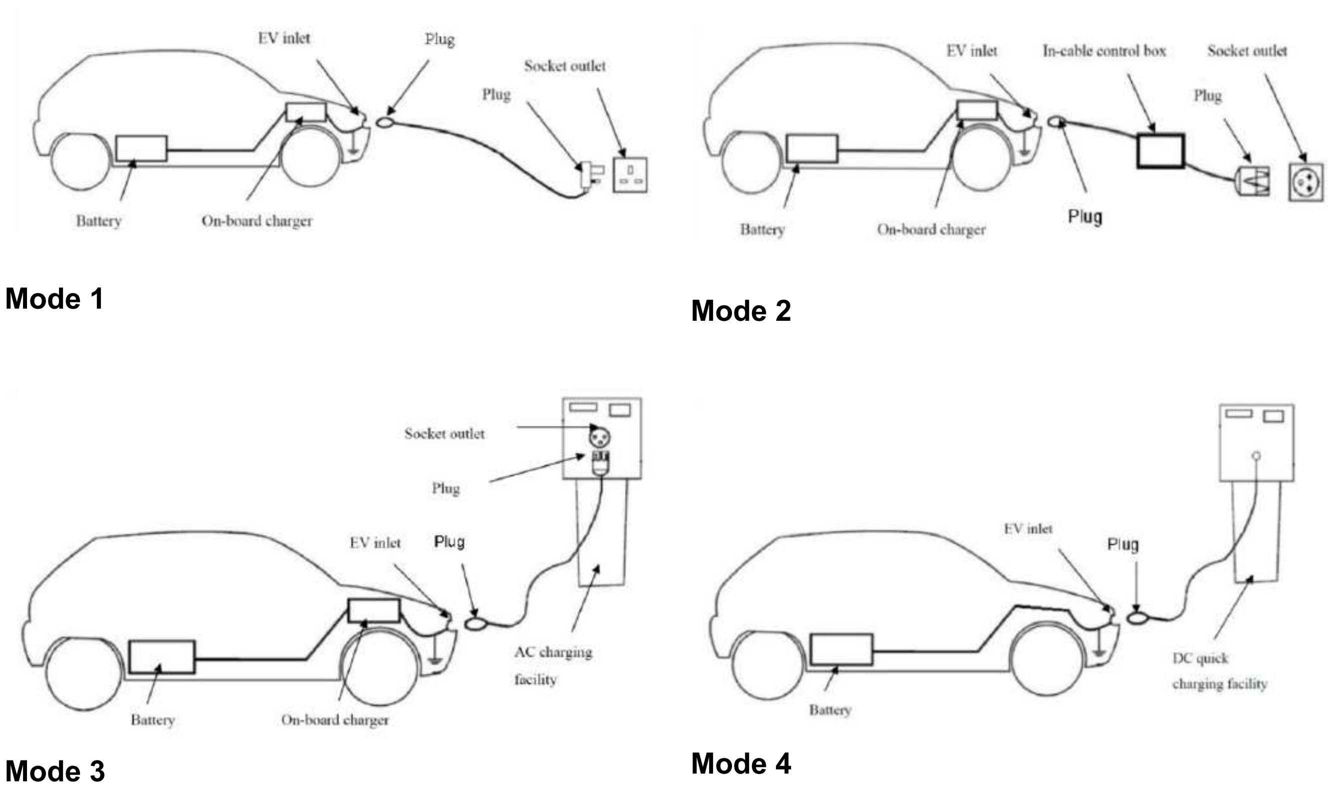


Figure 2.4: The different modes of charging (NEA, 2019)

2.1.2 Charging Levels

Internationally, EV charging can be categorized into different levels depending on the power rating and charging technology used. SAE has developed the EV charging level standards and the corresponding mode of charging, either on-board or off-board. The levels defined have their advantages and disadvantages and hence applicable accordingly.

Level 1 AC charging has a nominal supply voltage of 120 V and a current up to 20 A. They are primarily used in residential settings, which use an on-board single-phase charger and have a power output of up to 2.4 kW. It is a plug-and-play technology and does not require any installation, and hence less expensive. The charging time is exceedingly long, about 8 to

12 hours, due to the low charging power and hence ideally suited for residential applications. As the power rating is low and the usually the EV is charged during the night using these chargers, the peak energy demand is generally not affected.

Level 2 AC charging has a nominal voltage of 240 V and a current up to 80 A. It uses an on-board charger and has a maximum power output of 19.2 kW. It requires installation work and hence it is expensive as compared to level 1 AC charging. It is commonly installed in public parking areas, offices, malls, etc.

Level 3 charging, also known as DCFC (DC fast charging), has an off-board 3-phase charger that supplies the DC power directly to the battery bypassing the on-board charger. It has a nominal voltage of 200 V - 600 V and a current rating of up to 400 A, which gives a maximum power rating of 240 kW. They require a DC charging connector such as CCS and CHAdeMO as well as a compatible vehicle. Different communication protocols such as Power Line Carrier (PLC) and Controller Are Network (CAN) are used for the communication between EV and EVSE.

The levels of charging as per different standards are given in Table 2.1.

Table 2.1: Charging levels as per IEC 62196, IEC 61851 and SAE J1772 (Das et al., 2020)

	Level	Voltage (V)	Current (A)
IEC 62196	AC Level 1	120	16
	AC Level 2	240	32
	AC Level 3	250	32-250
	DC Level 1	600	400
IEC 61851	AC Level 1	120	16
	AC Level 2	240	80
	DC Level 1	200-450	80
SAE J1772	AC Level 1	120	16
	AC Level 2	240	32-80
	DC Level 1	200-450	80
	DC Level 2	200-450	200

2.1.3 Comparison between charging levels

As per the IEC 61851, EV charging is categorized into three levels. Level 1 and Level 2 are specified for AC charging, whereas Level 3/DC Level 1 is specified for DC charging. The benefits and drawbacks of each charging level have been summarized in Table 2.2

Level 1 charging does not require any installation work, and it comes with the EV. It uses an on-board charger to charge the EV battery with a maximum power of up to 2.4 kW. Due to low charging power and the time of charging, it reduces the peak energy demand. As the charging power is meagre, it takes a longer time, up to 8 to 12 hours, to charge the EV. It does not use any communication protocol between EV and EVSE, and also, there is no control over the charging power; it is just plug-and-play technology.

Level 2 is a moderate-speed charger that requires dedicated installation work, and hence it is expensive compared to level 1 charging. It has a communication protocol between EV and EVSE which receives data from BMS.

Level 3 charging uses an off-board charger that is part of EVSE, rather than an on-board charger, as in Level 1 and Level 2 charging. It is the fastest charging among these three and communicates between EV and EVSE using different communication protocols. Level 3 charging is most expensive as it requires highly specialized types of equipment and installation work. Another drawback is that level 3 charging is not supported for all EVs and hence limited in its use.

Table 2.2: EV charging level comparison

Charging Level	Benefits	Drawbacks
Level 1	• Cheap and convenient • No installation work • Minimum addition to peak energy demand	• Slowest charging • Longer charging time • No communication protocol • No charging control
Level 2	• Energy efficient • Easy to install • Provision of communication and control	• Expensive • Dedicated installation

Level 3	• Fastest charging speeds • Reduces range anxiety • Provision of charging control • EV and EVSE communication provision	• Highly expensive • Highly specialized equipment and installation • Not supported for all vehicles

2.1.4 Technical Details of EV charger

Commercially available EV chargers, also called EVSEs are a lot more than just a charging connector. In the case of an on-board charger, EVSE includes mechanical and electrical protection, environmental constraints, user interface and control, communication interface, etc. In the case of the off-board charger, EVSE includes a converter, converter control, filter, charging options in addition to the AC or on-board charger. The converter is the most crucial part of the charging system. In the case of an on-board charger, the converter is the part of the EV, and in the case of off-board charger, it is a part of EVSE (TI, n.d.)

The overall battery charger is represented in Figure 2.5 and Figure 2.6 with all the supporting components such as transformer, filter, switches, etc. The charging mode is selected as either constant current constant voltage (CCCV) or constant power constant voltage (CPCV). According to that, the PWM pulses are generated to be given to the converter. The current or voltage is controlled according to the mode of operation. The control algorithm for charging works in synchronization with Battery Management System (BMS) to control the charging mode during the charging and discharging process and it establishes the current and voltage limits.

In charging mode, the converter acts as a rectifier and converts AC power to DC. The AC filter and DC filter reduces the high-frequency current harmonics and ripples, respectively.

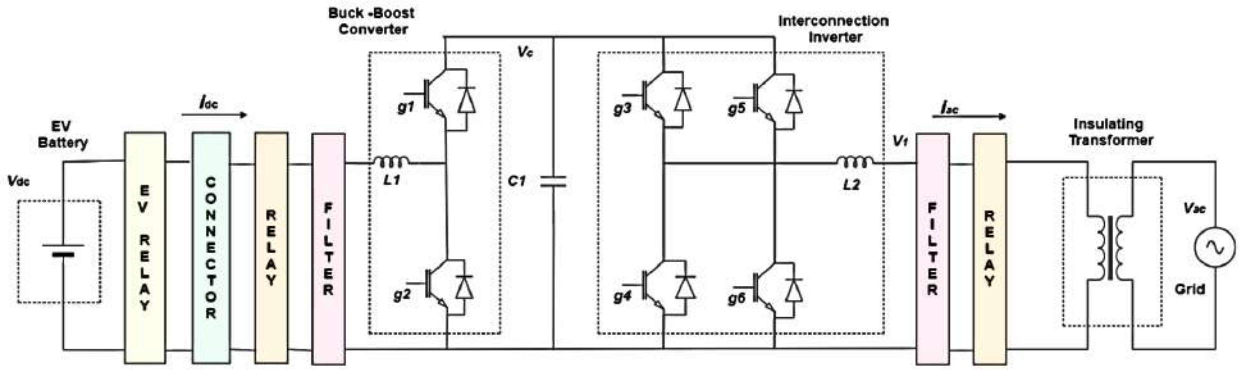


Figure 2.5: Electric Vehicle battery charger components

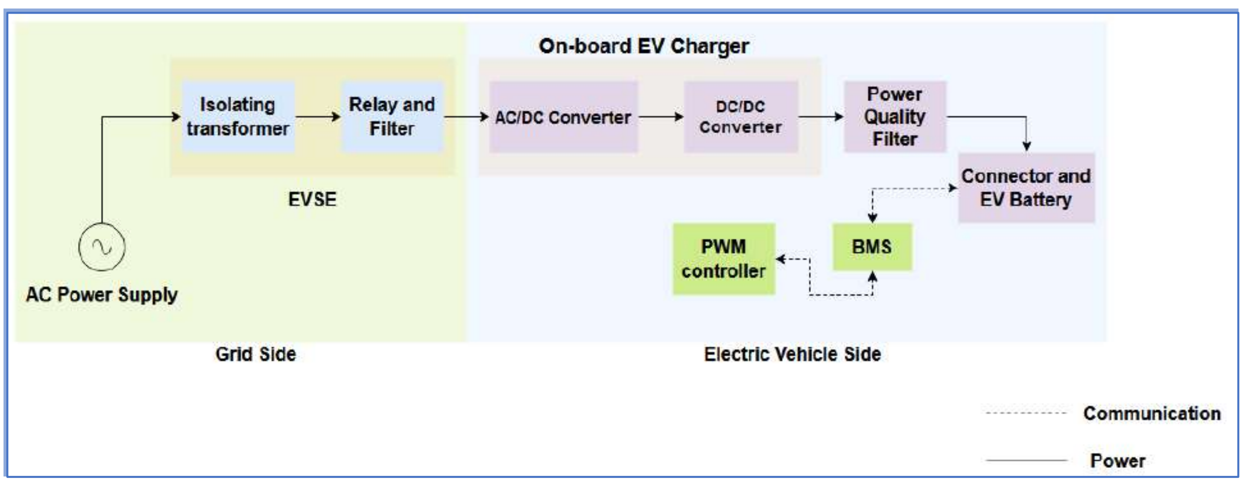


Figure 2.6: Block diagram of on-board EV charger

2.1.5 Converters and control for EV charging:

2.1.5.1 Level 1 and Level 2 charging

In Level 1 and Level 2 charging, the power is delivered at a 120 V or 240 V AC voltage. The current ranges from 16 A up to 80 A for residential and public outlets, respectively. The most popular connectors used for Level 1 and Level 2 charging are J1772 in America and Type 2 in many other countries. The EVSE is just a supervising system for the AC power delivery to EV and the EV determines the actual charging power/rate. The power available to use for EV charging is communicated to EV by EVSE.

The system requirements include a microcontroller that will communicate over a pilot line with the EV for determining the state of the relay. The power flow to the EV is enabled by controlling the contactors or power relays by the Gate driver/relay. Shunt resistors/Fluxgate sensors are used for real-time monitoring using current sensing. Amplifiers are signal sensing and generating devices. AC/DC converters and DC/DC converters provide power to relays, contactors, and MCU relays, respectively. The block diagram of Level 1 and Level 2 EVSE with its components for control and communication is shown in Figure 2.7

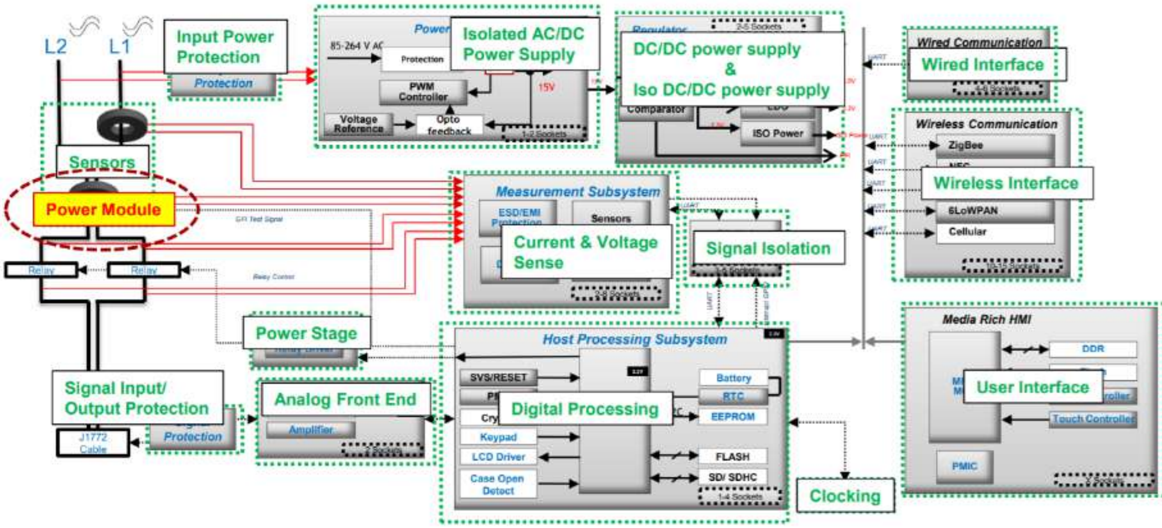


Figure 2.7: Block diagram and electronics inside an EVSE **(TI, n.d.)**

The AC/DC converter (Power supply) provides the stable DC voltage to the Regulator, which has different DC/DC converters that convert input DC into suitable voltage levels for further use. The 5 V supply is required for communication, whereas the ±12 V supply is used for the pilot signal.

The Host Processing subsystem, either Micro Processing Unit (MPU) or Micro Controller Unit (MCU), is loaded with all the software to communicate with EV, measurement, and run the system; thus, it is the core of EVSE. It can also be used for external communication.

The relay drivers actuate the driving relays that control the power and are typically large. They assure that the relays are driven correctly without any freewheeling effect of the electromechanical relays.

The pilot signal communication interface communicates the negotiation between MCU and the EV. A ±12 V supply with some sensing circuit and amplifier is used for the communication interface purpose.

Voltage and current are measured using potential transformers (PTs) and current transformers (CTs) to assure that EVSE is delivering the required power correctly to the EV.

If it is stuck at a closed or open position, the relay's state is detected using the voltages on both sides of the relay, and accordingly, corrective action is taken. This particular situation is unsafe and needs to be corrected immediately. All these signals are tied to the measurement subsystem. All the data is fed to the Host Processing subsystem through digital isolation to make appropriate decisions. Power line communication is used for communication interface in the public EV charging stations for EVSE and grid communication. Public EV charging installations have Human Machine Interface, a dedicated MCU or MPU with controllers and touchscreen.

2.1.5.1.1 Pilot Wire Communication Standard:

The charging power delivered to the EV from EVSE needs to be negotiated, and the pilot signal helps in this communication. A ±12 V Pulse Width Modulated (PWM) signal sent from the EVSE is read by the vehicle, and then the load is added to the Electric vehicle's state of charging. This provides a safe passage to the EV charging rather than just plug and play option. This process has several steps as

1.	+12 V is available on the pilot line when the EV is plugged in, and the power input from EVSE is zero.
2.	The pilot line voltage drops to 9 V when EV inserts the resistor, which confirms that the EV is plugged in. The EVSE responds by a 1 kHz PWM signal that varies between 9 V and -12 V on the pilot line to deliver the power to EV with a calculated duty cycle.
3.	The available power is determined by the duty cycle of the PWM, which is identified by adding the resistor in the pilot line, which drops the voltage from 9 V to 6 V, and then the actual power is turned on to begin the EV charging. The relays can be opened or closed by EVSE to enable the power flow.
4.	The charging stops when EV is charged completely, or EVSE cuts power, or an error signal sent by EVSE or EV stops power draw. The proximity wire can cut the power and help identify if the EV is plugged in or not.
5.	The pilot signal comes back to 9 V when the EV is done charging, and the connector can be removed from EVSE by opening the relays.
6.	The safety checks are added for extreme circumstances, which check if the system is working correctly or not, undertake diode checks, and give the error signal.

The EV and EVSE communication through pilot wire has been summarized in Table 2.3

Table 2.3: EV and connector communication using pilot wire.

State	Pilot high V	Pilot low V	Frequency	Resistance	Description
State A	12 V	NA	DC	NA	Not Connected
State B	9 V	-12 V	1 kHz	2.74 kΩ	EV connected (ready to charge)
State C	6 V	-12 V	1 kHz	882 Ω	EV charging
State D	3 V	-12 V	1 kHz	246 Ω	EV charging (ventilation required)
State E	0 V	0 V	NA	---	Error
State F	NA	-12 V	NA	---	Unknown error

Two separate formulas calculate the duty cycle:

For current from 6 A to 50A

Duty cycle= Available Amp/0.6

For current more than 50 A

Duty cycle= (Available Amp/2.5) + 64

The second option is for future robustness of the specification and is not implemented presently as there are only a few EVs that can take this type of AC input.

2.1.5.2 Level 3 charging

In Level 3 charging, DC output is directly fed to the battery of the vehicle as shown in Figure 2.8. These converters' operating range is 2 V to 450 V DC and charging currents up to 200 A. Due to this high charging rate, modern EVs charging time is reduced to 30 minutes. To enable this, direct communication with the vehicle, i.e., on-board charge management system, is required, which can be done with the power line communication or CAN network.

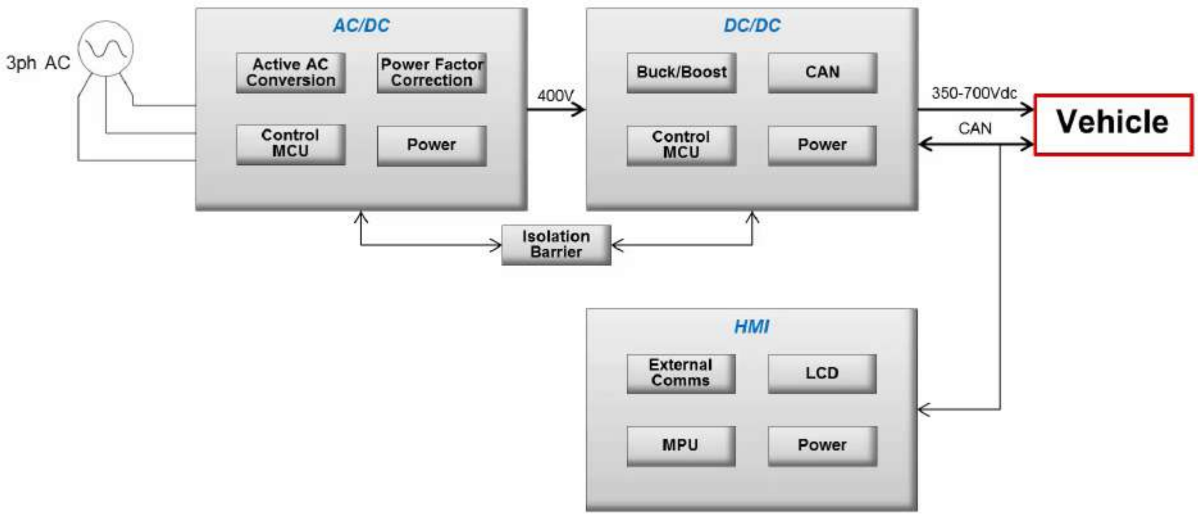


Figure 2.8: Block diagram of DC charging station **(TI, n.d.)**

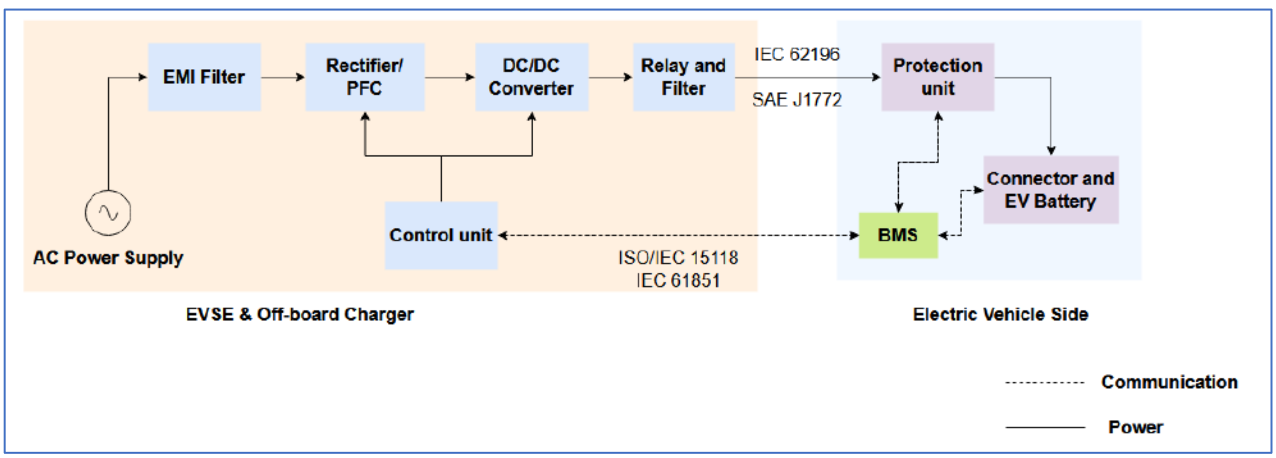


Figure 2.9: Communication and power flow between EV and EVSE

Level 3 EVSEs standards include the J1772 CCS (combined charging system), CHAdeMO, and Tesla Supercharger as shown in Figure 2.9. These system requirements include microcontrollers and digital power controllers to accurately control these AC/DC and DC/DC converters' power loops. Gate drivers and relays are used for power flow control. Gate sensors or current sensors are required for highly tuned feedback systems inside the DC/DC and AC/DC stages and communications via CAN or PLC at a minimum. Communication with the outside world via a different link may happen as most of these are going to be public charging stations. These are complicated systems with multiple parts operating at the same time.

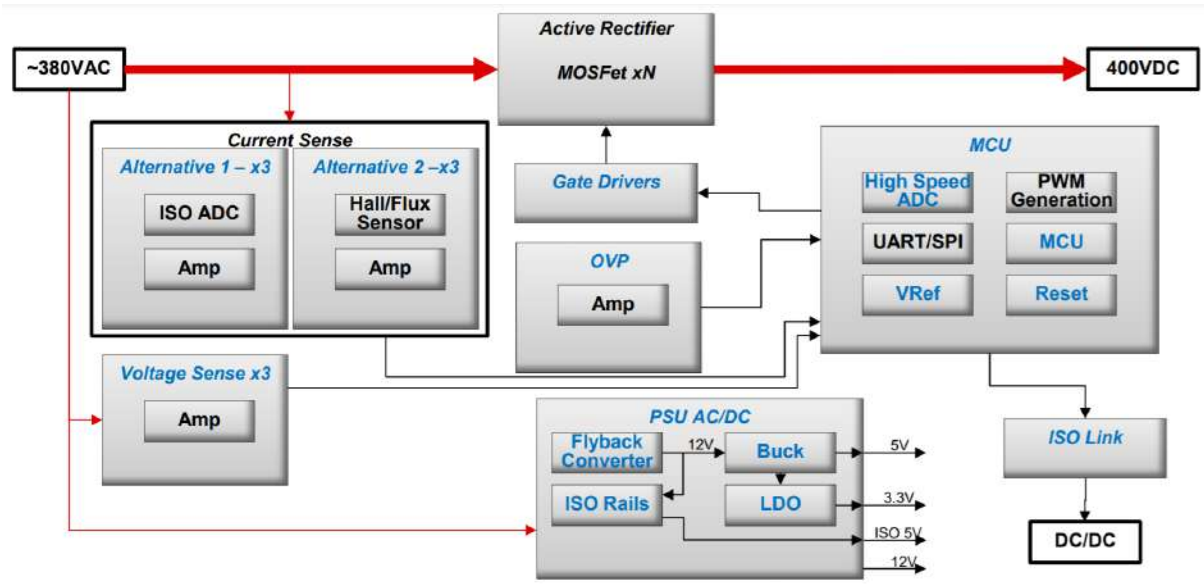


Figure 2.10: DC charging station AC/DC converter and control **(TI, n.d.)**)

The Block diagram as shown in Figure 2.8 is divided into three major sections which include AC/DC converter for converting AC power to 400 V DC, high voltage DC/DC converter to buck or boost according to the vehicle voltage levels required, and additionally, a human-machine interface, which will be an overall system supervisor. These designs have an inherent limitation on the amount of power built into an AC/DC or a DC/DC stage. To mitigate this, most methods use multiple stages in parallel to reach the power levels required by the vehicle itself.

Due to the required power level inside one of these power stages, AC/DC converter is more complicated than the simple bridge rectifier and transformer management. In this, use of active rectification arrangement called Vienna-style active rectifier is used. These will be MOSFETs on the AC line, which can switch dynamically to enable rectification. To run these MOSFETs, gate driver arrangement is required, either high-voltage or isolated gate drivers.

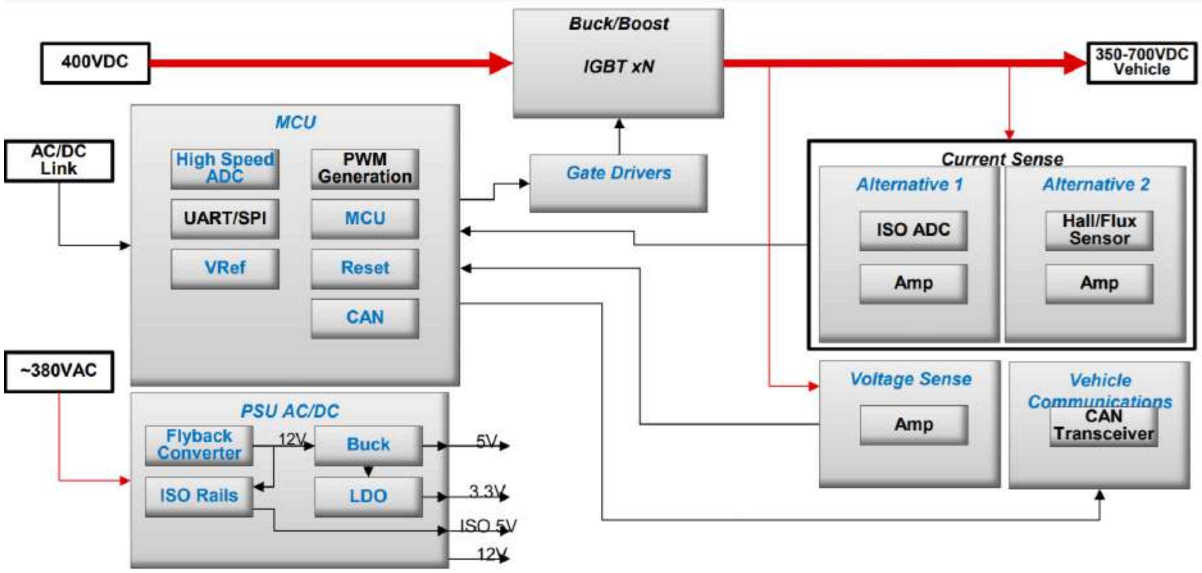


Figure 2.11: DC charging station DC/DC converter and control **(TI, n.d.)**

To obtain control of these effects, a microcontroller must operate in real-time, capable of running digital power calculations. These will require specific peripherals to keep this running effectively. A current sense arrangement can be made either with isolated ADCs or an inherently isolated sensor to run tight control loops.

Voltage sense amplification is required to sense the sinusoidal wave and its zero-crossing to switch on the active rectifier. A simple parallel power supply with a simple fly-back converter is required. Multiple low-dropout regulators (LDOs) are used to generate the different DC power lines. MCU must communicate to other parts via an isolated link. The rest of the system includes a DC/DC converter as represented in Figure 2.10. It has a dedicated microcontroller for running all of the digital power algorithms. Buck-boost stage using IGBTs is there to switch the power to the voltage required by the vehicle.

Buck converter, shown in Figure 2.12 is also known as step down converter, used in dc-dc switching. A step-down dc-dc converter lowers the output voltage as compared to the input voltage. This is done mainly by two switches; one controllable switch (Thyristor) is connected to the input voltage source. It is controlled by a gated pulse (Square wave), and the other switch, which is a diode, is connected to an LC filter which limits the ripple in the voltage and current. The controllable switch is controlled by pulse width modulation of the gated pulse, which can either be a time-based control or frequency-based control.

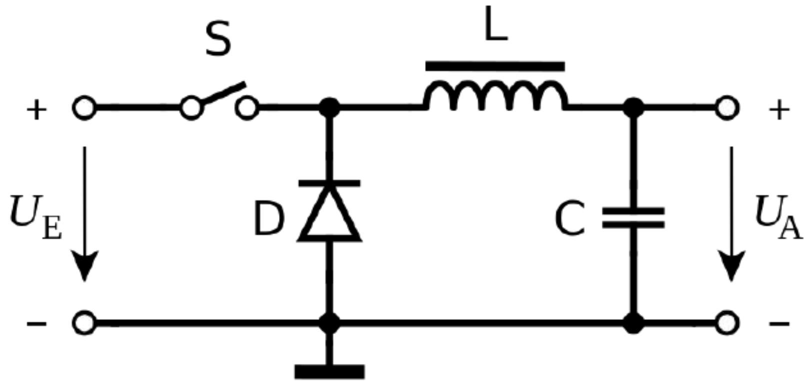


Figure 2.12: Buck converter

The flyback converter is one of the most popular converters found in the commercial product since it is a commonly used application with a low switch mode power supply. It is typically different from other converters where magnetizing inductance acts as a parasitic element, whereas here, the magnetizing inductance acts as a transformer for energy storage. This helps the flyback converter to act as both an isolating transformer and energy storage unit, wherein another converter a separate storage element is required. The converter schematic is simple; it consists of two switches, a transformer, and one capacitor, shown in Figure 2.13.

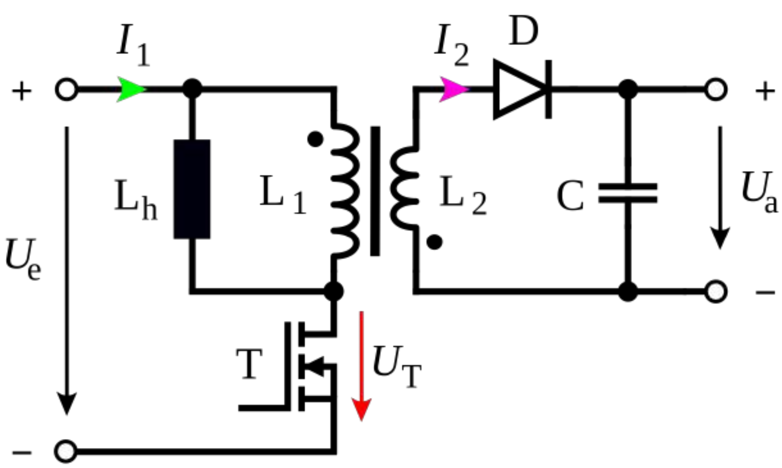


Figure 2.13: Flyback converter

Proper operation of IGBTs is achieved with appropriate gate drivers' current requirements. Digital power control loops require high-accuracy current sensing via isolated Analog to Digital Converter (ADC)s and voltage sensor arrangements.

Most DC charging stations will be publicly accessible, and for these, there is a need for a Human Machine Interface (HMI) system for the user to authenticate and interface with the charging station. To achieve this, there should be some type of microprocessor that will be an Advanced RISC Machines (ARM) class processor rather than simple MCU.

2.2 Charging speed

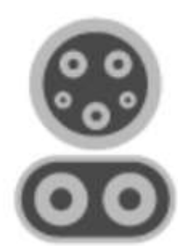
Here the term 'speed' is generally correlated to the output power of the EVSE, which translates to the amount of time required by the EVSE to completely charge an EV. As lower-powered EVSE would take a longer time to fill an EV with the same battery capacity compared with higher-powered EVSE, the EVSE can be demarcated as a slow, medium, or fast charger based on the power levels. However, different countries have different variations, and hence the classification based on charging speed is not unique. Charging speed is broadly categorized as shown in Table 2.4.

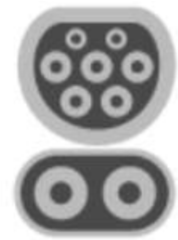
Table 2.4: Charging speed categories

Charging Speed	Power Output (kW)
Slow	Less than 3.7
Medium	3.7-22
Fast	Greater than 22

2.3 Connector Types

The different connector types used by different EV manufacturers are:

Type 1/Yazaki (SAE J1772, IEC 62196-1)	This connector used for single phase AC charging primarily in Japan and the USA,	
Type 2 (IEC 62196-2)	This connector type has been standardized by the European Union for use in AC charging (<22kW) charging	
Combined Charging System (CCS 1)	The connector can support EV charging through either AC charging using the Type 1 connector or through fast DC charging.	

CHAdeMO	Used exclusively for DC charging, the CHAdeMO connectors are used for fast DC charging	
Combined Charging System (CCS 2)	The connector can support EV charging through either AC charging using the Type 2 connector or through fast DC charging.	
GB/T DC Charger	Used predominantly in China, the GB/T charger is used for fast DC charging.	
Tesla Supercharger	Used exclusively for fast charging of Tesla manufactured electric vehicles	

The EV charging connectors are part of EVSE, plugged into the EV charging socket to charge the battery either by on-board or off-board charger. The charging connectors are differentiated as either AC/DC or by the power rating. The Indian standards of charging connectors derived from the international standards are given below.

Bharat AC-001 has a three-phase 415 V input supply and a single-phase AC output voltage of 230 V, 15 A as per IS 12360. It uses push-button type ON-OFF switches and uses the IEC 60309 industrial blue connector standard (3-pin female connector). EV and EVSE have no communication protocol incorporated in Bharat AC 001 charging technology. The EVSE and central management software use Open Charge Point Protocol (OCPP) for communication and authorization.

Bharat DC 001 uses three-phase 415 V AC input, to produce DC output voltage of 48 V/72 V and current of up to 200 A, which gives a power output of 10 kW/15 kW as per charger configuration type (either type 1 or type 2). The Bharat DC 001 (also known as Level 1 DC chargers) charging technology is defined as per the IEC 61851-1 and recommends GB/T

20234.3 connector, a China-based charging standard. EV and EVSE use CAN-based communication as per IEC 61851-24.

Practical conductive charging power curves

As reported in (Kane, 2021), the charging curve for the 2021 Tesla Model 3 Long Range (LR) AWD version with an 82-kWh Panasonic battery was tested and compared with the 2021 Tesla Model 3 Performance (P) with also an 82-kWh battery and the 2019 Long Range (LR) with an 80-kWh battery by a Norwegian EV user, Bjørn Nyland, at a Tesla V3 Supercharging station (250 kW) in Europe.

The charging in the newer performance version was noticeably slower, which could be attributed to an older version of the software. In contrast, the older 2019 Tesla Model 3 LR had the fastest charging so far when tested through the ScanMyTesla application. The charging power vs state-of-charge curve has been shown in Figure 2.14, in which it can be seen that the peak power of 250 kW is only available momentarily.

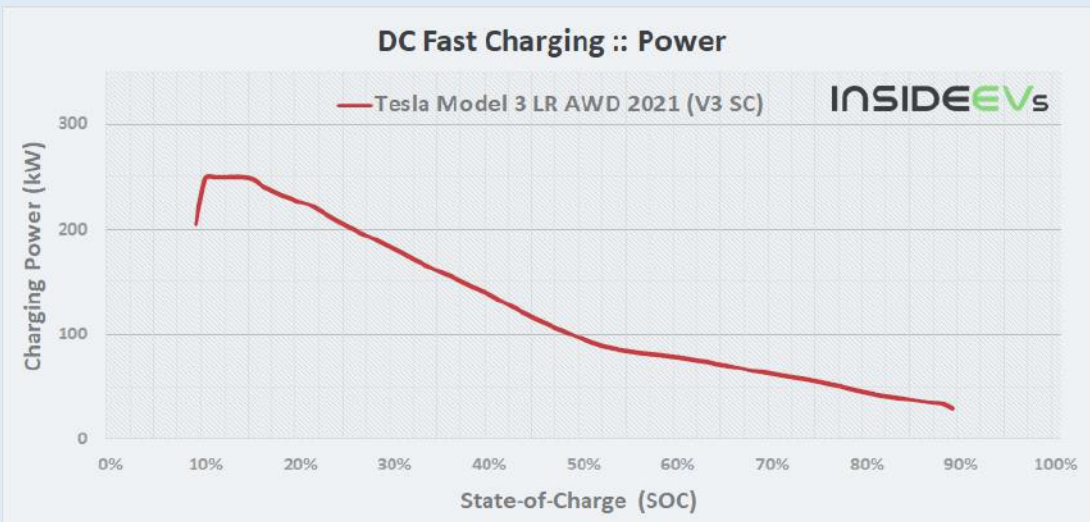


Figure 2.14: Charging power vs state-of-charge for the model (Kane, 2021)

Figure 2.15 shows the plot of the state-of-charge vs time elapsed. It took around 31 minutes for the batteries to reach a SOC of 80%, starting from 20%.

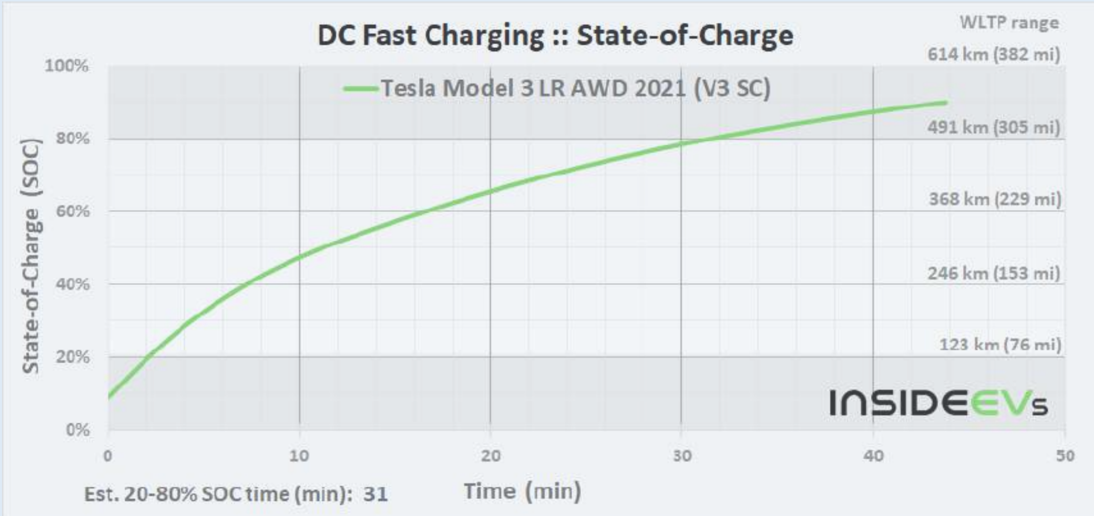


Figure 2.15: State-of-charge vs time elapsed during charging (Kane, 2021)

When it comes to the C-rate achieved during charging, which represents the charging power in relation to the total battery capacity, the peak value achieved was about 3.0C whereas the average value when charging from 20% to 80% was over 1.1C.

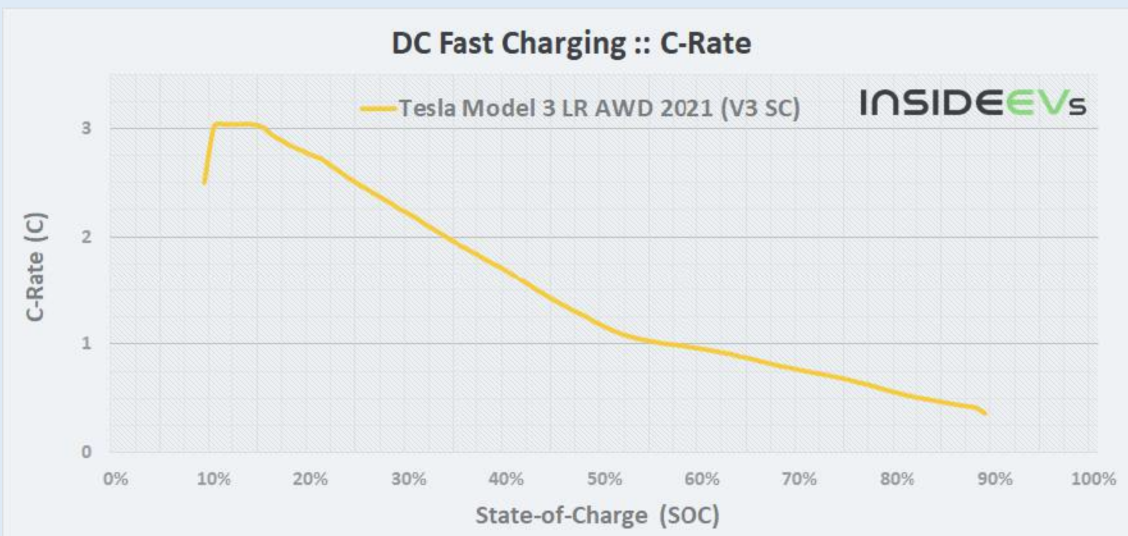


Figure 2.16: C-rate vs state-of-charge of the battery during charging (Kane, 2021)

The range replenishing speed of an EV is dependent on the energy consumption, which in turn is reliant on the use-case of the vehicle. Considering the Worldwide Harmonised Light Vehicles (WLTP) test cycle ranging over 614 km with an average battery capacity of 76.5 kWh (93% of the total battery capacity), it was assumed that the energy consumption was about 125 Wh/km. As a result, the effective mean range replenishing speed while charging from a SOC of 20% to 80% was calculated as 12.5 km/minute.

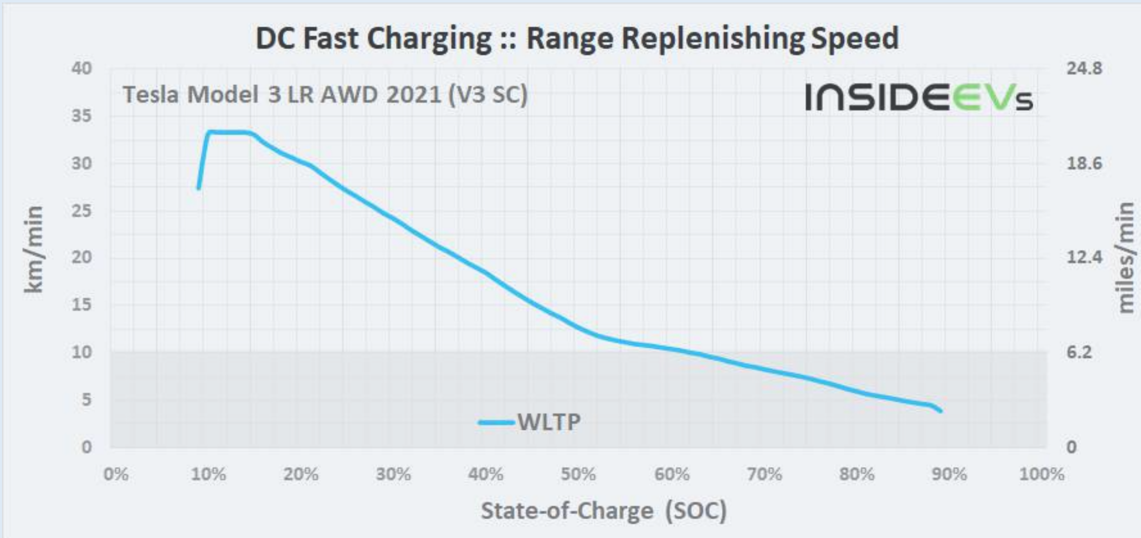


Figure 2.17: Range replenishing speed vs state-of-charge of the battery (Kane, 2021)

When compared with the other two models mentioned above in this test, Figure 2.18 shows that the 2019 model had a better charging speed despite having a slightly lesser battery capacity. The current long-range model can sustain the peak charging power for a shorter period, while the performance model was seemingly giving unexpected results with a slightly lagging curve.

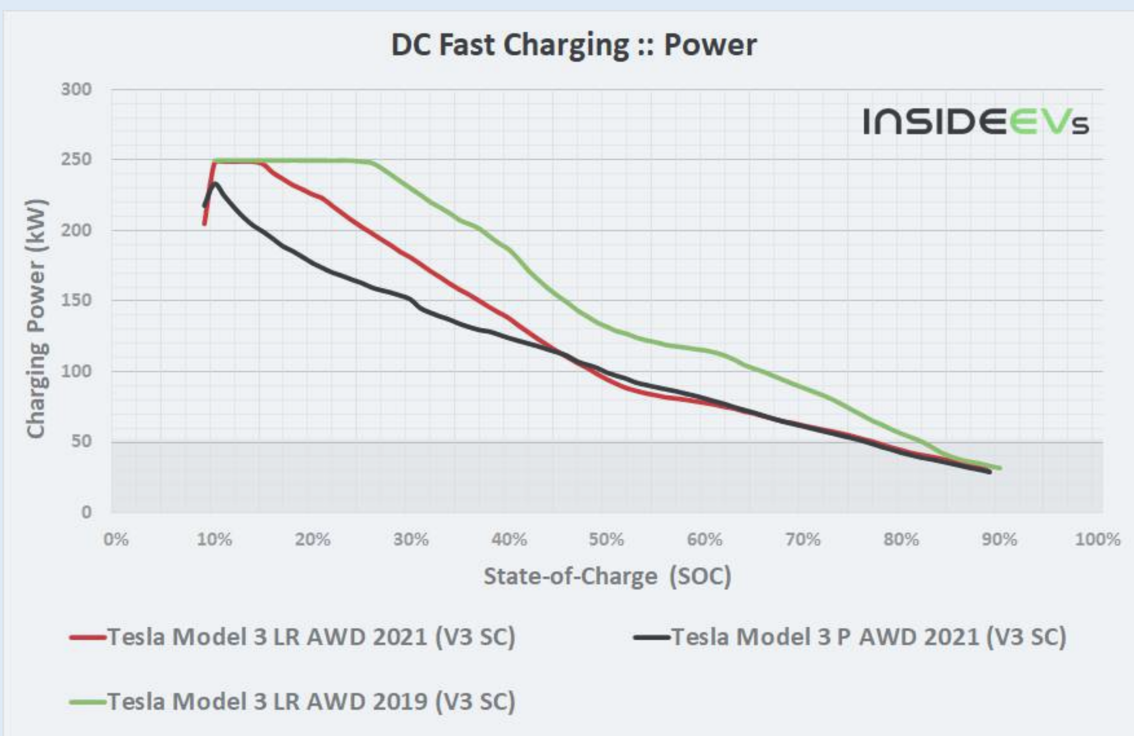


Figure 2.18: Comparison of the SOC vs charging power of the three mentioned models (Kane, 2021)

Subsequently, three more models were added to the above comparison. Again, the tallied results imply that the 2019 models showcased better results than their 2021 counterparts, with the peak value lasting for almost 30% SOC, given in Figure 2.19.

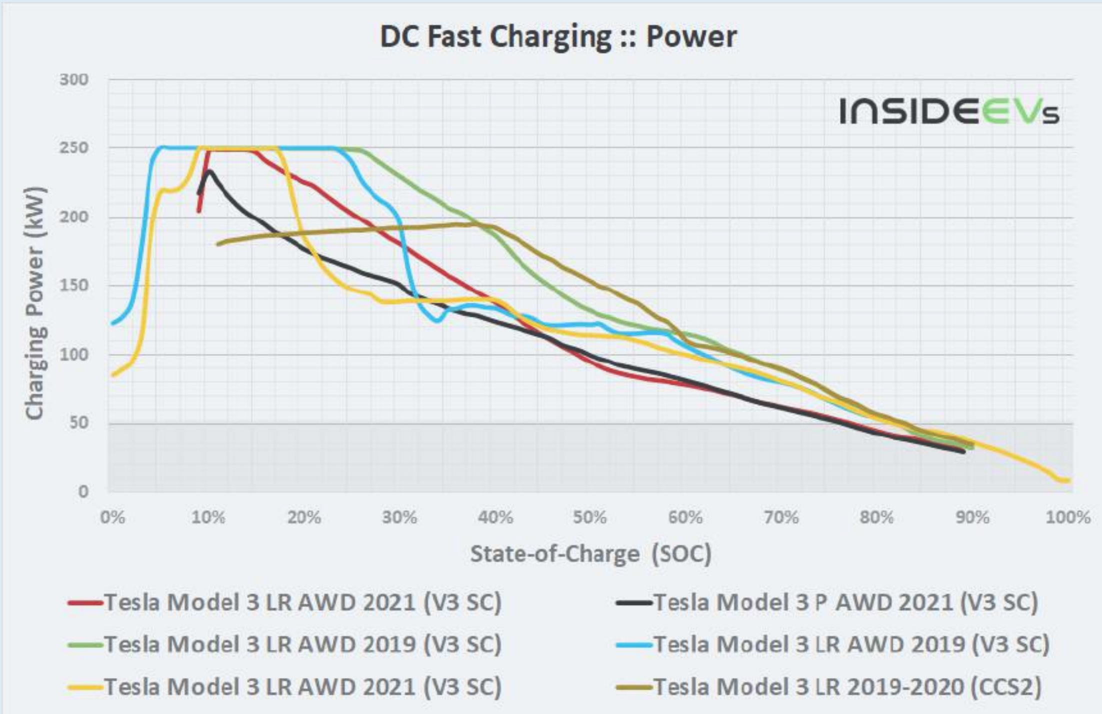


Figure 2.19: Comparison of SOC vs charging power for the six different models of Tesla Model 3 (Kane, 2021)

The C-rate comparisons of the same models at Tesla V2 Superchargers are shown in Figure 2.20. The 2021 models go from 20% to 80% SOC in 31 minutes, whereas the 2019 ones did it in 22 minutes.

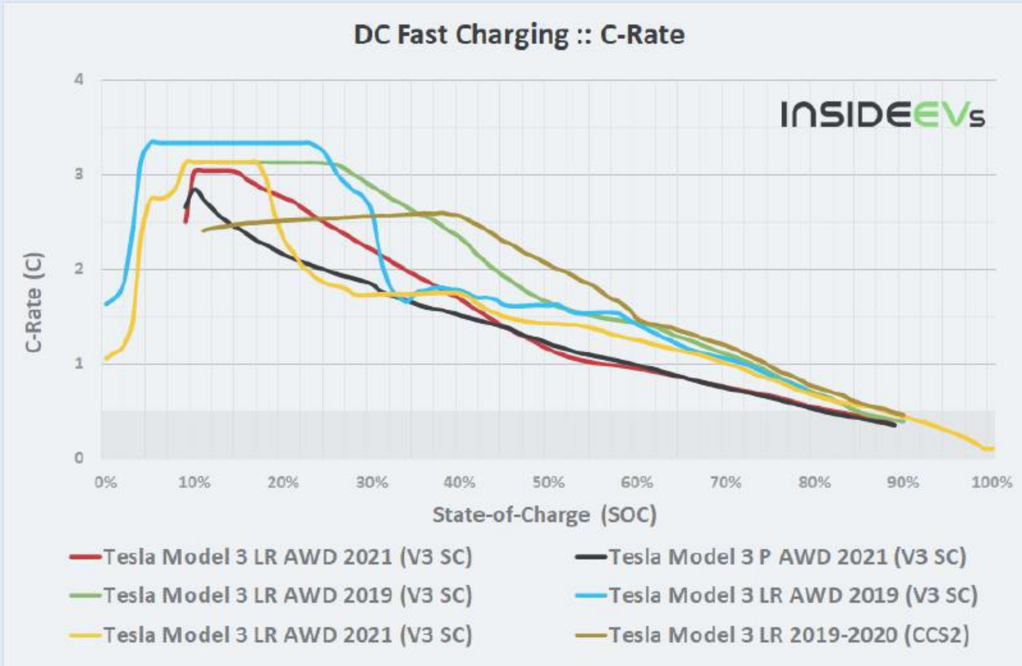


Figure 2.20: SOC vs charging C-rate for the six different models of Tesla Model 3 (Kane, 2021)

When it comes to the comparison of the range replenishing speeds, the 2021 models had a higher WLTP range and thereby were able to offset the low charging power, as shown in Figure 2.21.

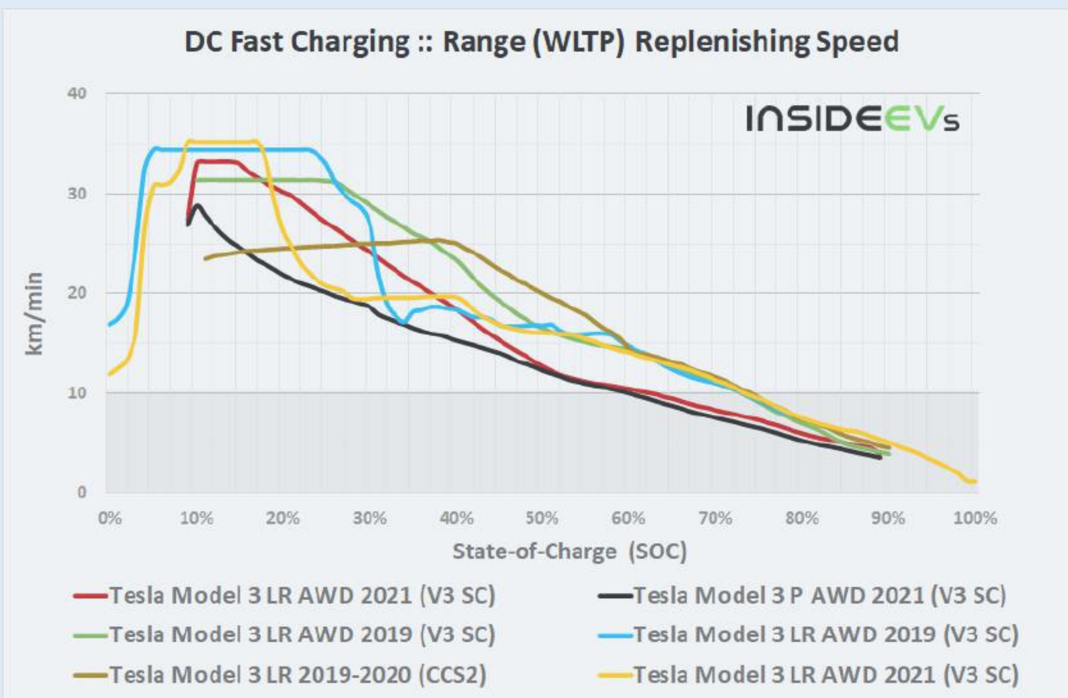


Figure 2.21: SOC vs range replenishing speed for the six different models of Tesla Model 3 (Kane, 2021)

Hence, it can be observed that the earlier models from 2019-2020 provided better charging performance with a broader range of peak power. Although some of it could be due to the particular atmospheric conditions during the charging sessions, it is unknown whether the shortfall in charging strength came from the compromise by Tesla to improve energy density and/or efficiency, longevity, or cost of the batteries, in the latest editions of its cars. One of the potential reasons that Panasonic has cited for the slower charging in the newer models is the relatively diminished use of cobalt in their batteries with the company's aim to further reduce its use with an ultimate goal of cobalt-free batteries in a few years (Oberhaus, 2020).

2.4 Wireless Charging:

The Wireless Power Transfer (WPT) is achieved using near-field electromagnetic coupling (non-radiative). WPT has two types, namely inductive and capacitive. In the inductive WPT, conducting coils are coupled using the electromagnetic field, whereas conducting plates are coupled using an electric field in capacitive WPT.

2.4.1 Inductive WPT

The WPT technology has a transmitter side and a receiver side power electronic system as illustrated in Figure 2.22. The transmitter side consists of a high-frequency inverter with a current gain and compensation network coupled to the receiver side by a magnetic coil. The receiver side has a voltage gain and compensation network connected to the high-frequency rectifier. The inductive WPT requires ferrite cores for guiding and shielding magnetic flux. The frequency of the system is kept under 100 kHz to limit ferrite losses. This results in large coils, making it bulky; hence, the cost and low power transfer density determine the commercial viability of inductive WPT. The inductive online electric vehicle (OLEV) charging system includes:

Online EV Charging System

A **power converter** that converts the 60/50 Hz AC power from the grid to a 20 kHz AC power available at the road-embedded power tracks. 20 kHz frequency has been computed for optimal magnetic field coupling, thus making efficient power transfer from the road embedded power transmitter to the vehicle embedded receiver.

Roadway Infrastructure consists of road-embedded power tracks installed in multiple segments at selected locations of the route. There are two power lines with up to 200 A current flowing in opposite directions to form a loop and generate DC power for the electric motor in EV. For efficient power transfer, the only segment turned on is the segment under the vehicle.

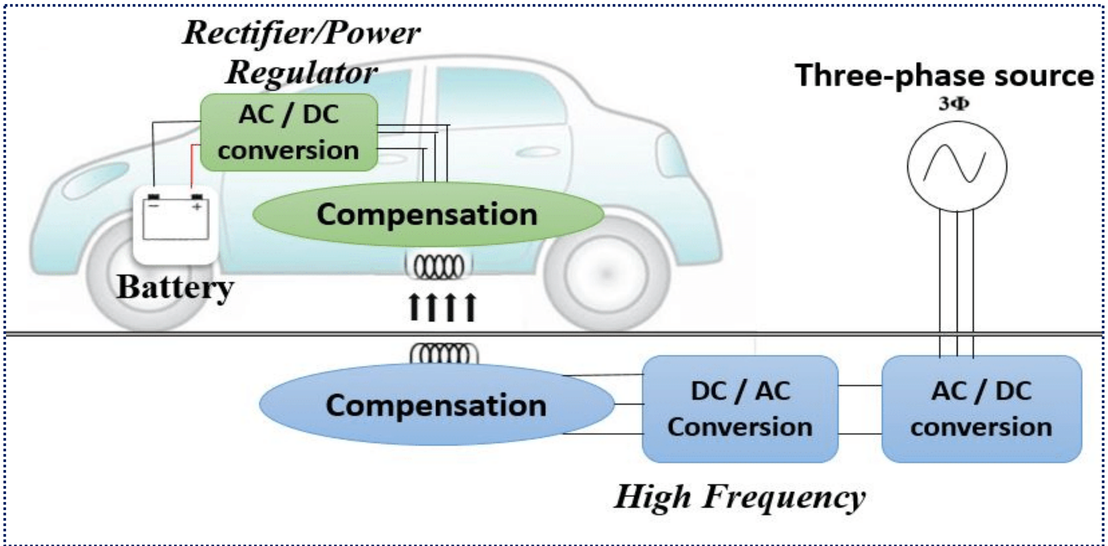


Figure 2.22: Inductive wireless power transfer **(Mohamed et al., 2017)**

2.4.2 Capacitive WPT

Due to the electric field's directed nature, the need for electromagnetic shielding is eliminated in capacitive WPT (Figure 2.23) and hence possesses a massive advantage over inductive WPT. The absence of ferrite makes way to use high frequency which results in smaller size, making it less expensive. Whereas the use of high frequencies makes it challenging to design the system. The main challenge faced by the capacitive WPT is meeting the electromagnetic safety with high-power transfer density at high efficiency (F. Lu et al., 2018).

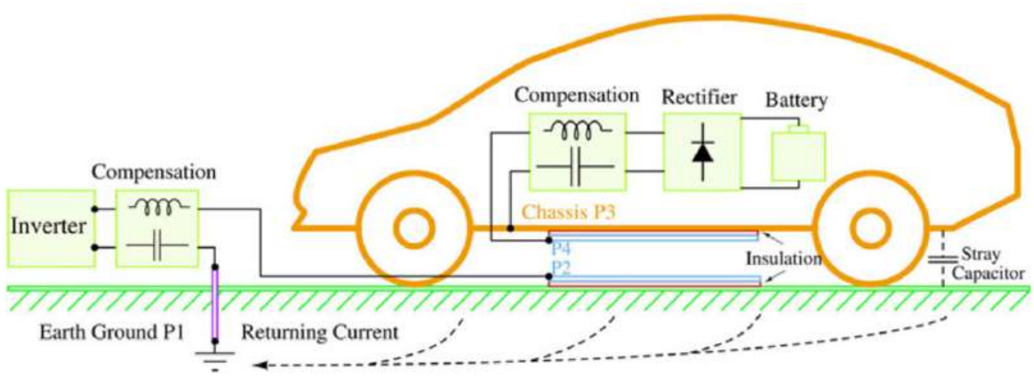


Figure 2.23: Capacitive wireless power transfer (F. Lu et al., 2018)

2.4.3 EV Wireless charging standards

The main barrier holding the commercialization of high-voltage and high-power WPT for EV charging are electromagnetic (EM) limits, safety criteria, efficiency, and test setup.

Standardization provides a compatible charging station to all EV owners. Some of the wireless EV charging standards with their description are tabulated in Table 2.5. The total WPT system is included in the IEC 61980-1 standard from the supply network to charging the battery or any equipment at the standard supply of 1000 V AC or 1500 V DC (Shivanand et al., 2019).

SAE TIR J2954 (TIR-Technical Information Report) is the first standard developed by SAE in WPT for an EV charging application specifically for SWC. Some factors like coil definitions, frequency band, interoperability, and electromagnetic compatibility/electromotive force (EMC/EMF) limits of this standard allow any vehicle to charge from its wireless home charger with the same charging ability (Shivanand et al., 2019).

Critical standards for wireless charging shown in Table 2.5. Vehicles which are capable of being charged wirelessly should also be able to be charged by SAE J1772 plug-in chargers. SAE J2954 is used for stationary applications. SAE J2954 is used for interoperability, performance, and emissions testing (Shivanand et al., 2019).

Table 2.5: Wireless EV charging standards (Shivanand et al., 2019).

Standard Developer	Standard Name	Description
IEC	IEC 61980- 1Ed2.0	Electric Vehicle wireless power transfer (WPT) System Part 1: General Requirements
IEC	IEC 61980- 1/IAMD I Ed1.0	Electric Vehicle wireless power transfer (WPT) System Part 1: General Requirements
IEC	IEC 61980- 1/COR1A	Electric Vehicle wireless power transfer (WPT) System Part 1: General Requirements
SAE	J2954SAE	Wireless charging Electric and Plug-in Hybrid vehicles
SAE	J2954_201605	Wireless power transfer for light-duty plug-in /Electric vehicles and Alignment methodology
SAE	J1773_201406	SAE electric Vehicles inductively coupled charging

2.5 Battery swapping

Battery swapping is a straightforward and rapid process. It takes a few minutes to change the discharged battery with a fully charged one. However, depending on the vehicle model there are different techniques of battery swapping methods. The two different types are,

- Chassis type battery swapping where the loading and unloading of battery is carried out from underneath the vehicle.
- The battery packs are replaced from the side or rear of the vehicle.

Most electric 4 wheeler (e-4W) have their batteries placed at the base of the chassis and so, the replacement of their battery packs requires specialized equipment. This is not the case in most of the 2W and 3W models, whose batteries are easily accessible. Hence battery replacement from a technical standpoint is viable for 2W and 3W but a bit difficult in case of 4W. In 2013, Tesla presented a battery swapping technology which was able to replace the battery of a Model S in around 90s. However, they faced several issues due to which they never scaled up the technology and only operated a sole battery swapping station in California. One disadvantage of this technology is that, as the battery pack lies in the bottom of the chassis, it is rigidly attached with a multitude of bolts and screws which makes the swapping process complicated, as shown in Figure 2.24.

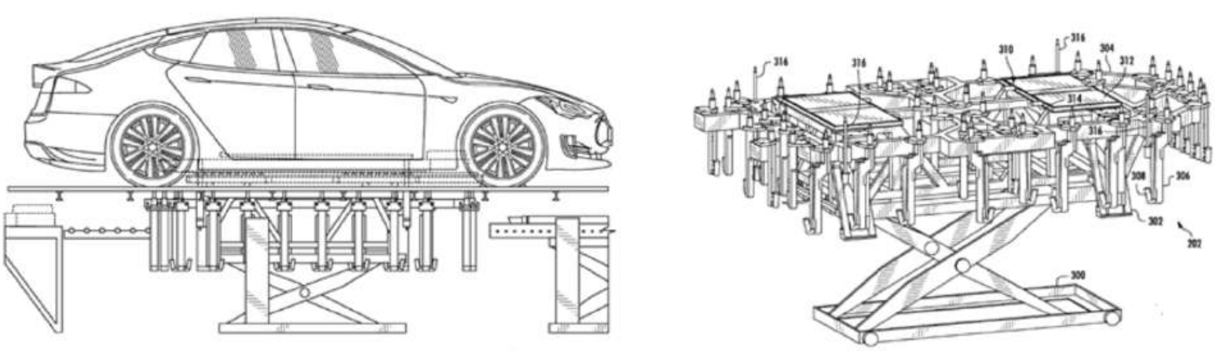


Figure 2.24: Tesla's battery swapping technology **(WIPO, 2016)**

If the battery ownership is eliminated, then the EV capital cost reduces rapidly. The off-peak hours can be effectively utilized to charge the discharged batteries reducing the peak energy demand (Upadhyay, 2017). The battery-swapping station can act as storage hubs and can help the grid utility in power system management as shown in Figure 2.25. Battery swapping stations can provide voltage support, regulation reserve, and maximize profits. However, the battery swapping technology poses several disadvantages due to compatible battery pack design, massive investment in the infrastructure for charging, and the number of batteries. Also, there is an issue of battery ownership at the time of swapping and battery degradation (Pon Paulraj, 2020).

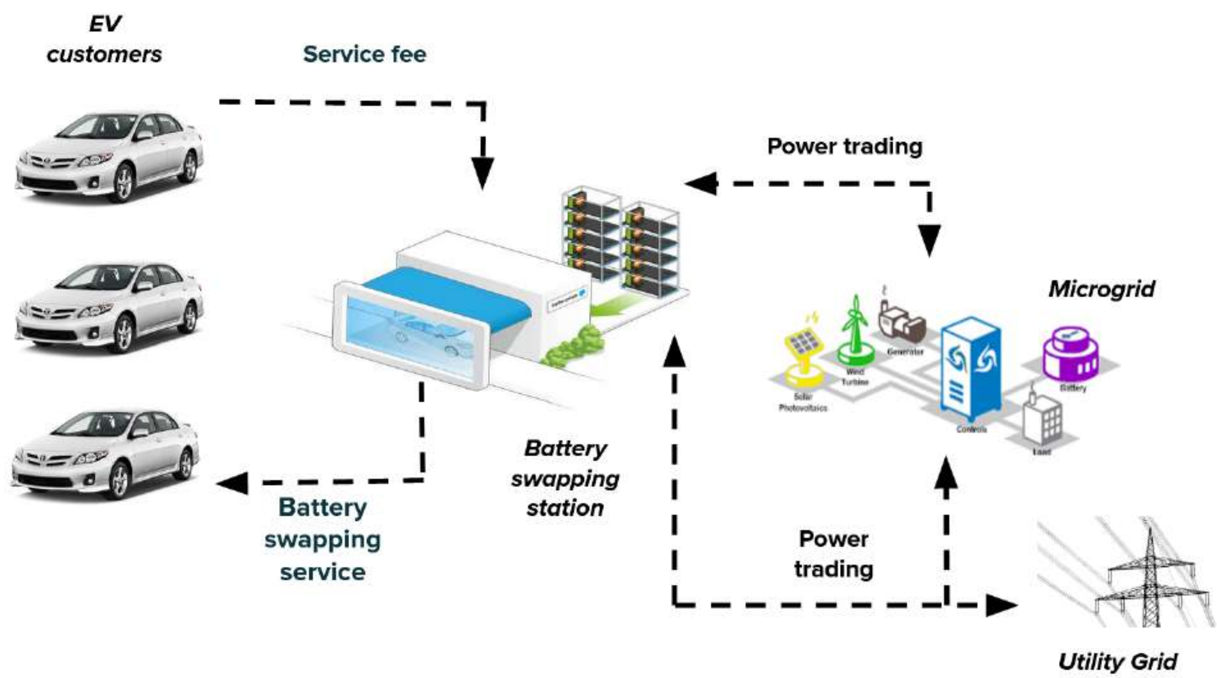


Figure 2.25: Battery swapping station and components

Chapter 3: Standards for EV Charging

Different regulatory bodies worldwide provide various standards with regard to the operation of electric vehicles (EVs). Institute of Electrical and Electronics Engineer (IEEE), International Organisation for Standards (ISO), International Electrotechnical Commission (IEC) and Society of Automotive Engineers (SAE) are leading regulatory bodies that provide standards for every entity in the EV ecosystem. This standard covers the complete spectrum of design and construction of EV charging station, EV charging/discharging, safety, and communication. It mentions the technical, testing, and design aspect of entities in the EV ecosystem. The standards are classified as charging standards, charging station standards, connector standards, and safety standards. These standards are discussed and explained below.

EV charging is divided into two types based on power transfer technique: Conductive charging (wired charging) and inductive charging (wireless charging). It further gets categorised into AC and DC charging based on the type of power transfer. IEC 61851 and SAE J1772 are the standards for conductive charging, whereas IEC 61980 and SAE J2954 are for inductive charging. This report majorly covers conductive charging.

3.1 International Standards

3.1.1 EV Charging Standards

3.1.1.1 IEC 61851

IEC 61581 covers conductive AC and DC charging for on-board and off-board charging equipment for supply voltage up to 1000V AC and 1500V DC to charging equipment. It covers mechanical, electrical, communication and performance requirements of EVSE. The electrical aspect of EVSE comprises its different characteristic and operating modes, connection specification between EV and EVSE, and its safety requirements.

EVSE is classified based on charging modes viz., Mode 1, Mode 2, Mode 3, and Mode 4. These charging modes are detailed in Table 3.1. Mode 1 is a simple connection charging with EV and home socket. The controlling pilot pin is not present in this connection. Hence, Mode 1 EVSE does not allow smart charging based on power modulation but provides an additional protective earth conductor for safety. This charging mode is prohibited in some places and has further limitation in current value and grounding aspects. Specification parameters of different modes are given in Table 3.1. Mode 2 is operating at higher voltage values for single-phase and three-phase supplies. It connects EV with a socket with a control pilot pin and has a dedicated system for personal protection from electric shocks. It is limited in use in some countries based on values of current, voltage and location. Mode 3 is applicable for higher rating EVSE with a control pilot pin for controlled charging. It has a protective earthing conductor for the EV socket or vehicle connector. Mode 4 is a connection of EV to DC EVSE with a control pilot pin. It also has a protective conductor connected to the vehicle connector.

There are some mandatory functionalities of Mode 2, 3, and 4 related to EVSE operation, given below.

a. Continuous protective conductor checking

b. Verification of proper connection between EV

c. Energization and de-energisation of power

d. Maintaining current within maximum limits.

The standard also provides communication requirement for EVSE. Communication is optional in Mode 1, Mode 2, and Mode 3. Mode 4 is required to have digital communication provided in IEC 61851-24 to allow the control of EVSE by EV. Different parts of EVSE shall comply with some specific IP rating requirements and standards on the protection aspect. It mentions construction requirements and test with the installation and marking manual.

Table 3.1: Charging modes in IEC standard

		IEC standard			
		Mode 1	Mode 2	Mode 3	Mode 4
Voltage (V)	1-ph	250	250		DC 200-600
	3-ph	480	480	480	
Current (A)		16	32	250	400
Power (kW)		13.3	26.6	184.4	240
Connector		Household	Household	IEC 62196 Type 1-3	IEC 62196 Type 2

Standard specifies in the detailed description of operation, working of control pilot pin, test procedures. IEC 61851 has sub-sections focusing on particular aspects. Some subsections of IEC 61851 related to conductive charging are given below in Table 3.2.

Table 3.2: Sections in IEC 61851 standard **(IEC, n.d.)**

Sub-section	Brief information
IEC 61851-1	Charger and plug setup for EV charging
IEC 61851-21-1	Electromagnetic compatibility (EMC) requirement for on-board conductive charging using AC/DC supply.
IEC 61851-21-2	Electromagnetic compatibility (EMC) requirement for off-board conductive charging using AC/DC supply.
IEC 61851-23	Requirement of DC charging station
IEC 61851-24	Digital communication between DC charging station and EV

3.1.1.2 SAEJ1772

It provides the design and specification of AC and DC charger. Rating of the equipment in charging infrastructure is mentioned for AC and DC charging (Falvo et al., 2014; TI, 2019) . The charging levels and ratings are also given with the limiting parameters (circuit breaker) for the particular ratings. The standards cover detailed information on control pilot pin, working, and signal flow for controlling the charging using EVSE. The charging level information with the specification of current and voltage is given in Table 3.3:

Table 3.3: SAEJ1772: Charging levels with ratings

Parameter	SAE standard		
	Level 1	Level 2	Level 3
Voltage (V)	120	240	200-600
Current (A)	16	80	400
Power (kW)	1.92	19.2	240

3.1.1.3 IEC 61980

This standard is for wireless power transfer from charging plates to EV battery for supply voltage rating up to 1000 V for AC and 1500 V for DC (Das et al., 2020). It is implemented using on-site storage equipment.

3.1.1.4 SAE J1773

This standard specifies the minimum charging requirement for inductive charging. The standard provides explicitly separate charging requirement for manually connected and software-controlled inductive charging station (Das et al., 2020).

3.1.1.5 SAE J2954

It is the first wireless charging standard that covers charging up to level 2 (7.7 kW). In recent years, SAE J2954-recommended practices provided standards for charging up to level 3 (11 kW) (Das et al., 2020). It provides a standard testbed for performance analysis and driving assistance for parking, payment and autonomous charging.

3.1.1.6 GB/T 20234

The Guobaio (GB/T) standard is issued by the Standardization Administration of China, the Chinese national committee of ISO and IEC, for providing a standard guideline for the plug, socket and connector for EV conductive charging. The additional role of the standard is to provide testing methods and testing specification for conductive charging at rated AC voltages of up to 690 V, 250 A, 50 Hz and rated DC voltages of 1000 V DC, 400 A (ChineseStandard.net, 2016). It is applicable for conductive AC or DC EV charging.

3.1.2 Plug, Connector, And Socket Standard:

This standard describes the design, operation, and control of plug, connectors, etc. required for connection of EVSE to EV inlet. Standards provided by different regulating bodies for EV charging connector equipment is given below.

3.1.2.1 IEC 62196

IEC issued this standard for providing a detailed understanding and standardised dimensions of charging accessories (IEC, 2014). Dimensionality and construction of connectors and sockets are discussed in detail. Rated voltage and current values for signal control purpose are provided. Details related to protection from electrical shocks, tests circuit and procedure, interlocks, degree of protection, normal operation, and temperature rise are also covered in the standard. Different parts of IEC 62196 standards and brief information of it is given in Table 3.4.

Table 3.4: Sections in IEC 62196 standard

Standard	Explanation
IEC 62196-1	It provides the general requirement of plugs, sockets, connectors and inlet for conductive charging

IEC 62196-2	It covers dimensional compatibility and interchangeability requirements for AC pin and connector accessories
IEC 62196-3	It covers dimensional compatibility and interchangeability requirements for DC pin and vehicle coupler

3.1.3 Miscellaneous

3.1.3.1 IEC 60364

Role: The role of the standard is to provide the fundamental principle, assessment, definition, safety, and protection of low voltage electrical installation. Different sections of the standards provide standards for protection against electrical shocks, protection against the thermal effect, overcurrent, voltage, and electromagnetic disturbances. It also provides safety standards for isolation, switching, control, and wiring system.

Application: It is applicable for the safety and protection of the EV and the charging system.

3.1.3.2 SAEJ2293

It gives a power requirement for conductive AC, conductive DC, and Inductive charging. Communication requirement and network for EV charging are also mentioned in the standard. It mentions the energy transfer system and allocation of EV and EVSE.

3.1.3.3 SAEJ2836

It provides information regarding testing infrastructure and case studies of communication between EV and charging station. The subsection of the standard SAEJ2836/1- 2 gives the test cases with detailed description about communication between EV and charging station, SAEJ2836/3 provides the test case in which EV communicate as a Distributed Energy Resource (DER), and SAEJ2836/4-6 provides the test case for wireless charging and diagnostic.

3.1.3.4 SAEJ2931

This standard provides the digital communication requirement for a smart EV environment in between EV and EVSE. Subsection SAEJ2931/1 covers basic architecture and communication requirement, SAEJ2931/2- 4 gives the physical layer implementation with narrow and baseband OFDM. The communication interface is achieved through Home Area Networking (HAN) (Bohn, 2013).

3.1.3.5 SAEJ2954

It focuses on the wireless charging specification of charging station up to level 3 (11 KW) (Campi et al., 2019). The standard provides the testbed for the EV manufacturers to check the performance of the new product. It also provides autonomous charging and seamless parking.

3.1.3.6 IEEE1547

Standard provides requirements and information about performance, operation, safety, and testing of interconnected DERs with grid up to 10 MVAR at point of common coupling (Basso et al., 2015). Subsection IEEE P1547.2 acts as a user guide for IEEE 1547 by mentioning the technical requirement and details of the application. IEEE P1547.3 provides details on monitoring and data exchange between DER and utility to achieve interoperability. IEEE P1547.4 provides details on design and operation, and integration aspect. It also mentions the guidelines to operate the system in an islanded mode of operation.

3.1.3.7 NFPA 70

It covers the wiring and safety-related requirements; in addition to that, it also focuses on the specification of conductors and other equipment (NFPA, n.d.).

3.1.3.8 SAEJ2836

It provides information regarding testing infrastructure and case studies of communication between EV and charging station. The subsection of the standard SAEJ2836/1- 2 gives the test cases with detailed description about communication between EV and charging station, SAEJ2836/3 provides the test case in which EV communicate as a DER, and SAEJ2836/4-6 provides the test case for wireless charging and diagnostic.

3.2 Indian Standards

AIS 138 part 1 and AIS 138 part 2 are the Indian charging standards for conductive AC and DC charging. In preparation of standards, considerable assistance has been taken from international standards IEC 61851, IEC 61851-21, IEC 61851-22, IEC 61851-23, and IEC 61851-24 describing the requirement of conductive AC and DC EV charging and communication.

3.2.1 AIS 138 part 1: Electric vehicle conductive AC charging

The standard covers general system requirements, ratings, safety, protection, and communication aspects for conductive AC charging. Definitions of every component in conductive AC charging is explained. It is applicable for rated supply voltage up to 1000 V within +/-10% of tolerance and rated frequency up to 50HZ with +/-3% tolerance band (AIS, 2017). Various AC charging modes with different connection interface have been explained in detail below. Conductive AC charging is categorised into two modes: AC slow charging and AC fast charging.

3.2.1.1 AC slow charging

It is single-phase AC charging with a current rating of up to 15A, IEC 60309 connector shown in Figure 3.6 (household connector), protection earth conductor, personnel protection against shock, and mandatory safety of EVSE. Pin information and nomenclature of the IEC 60309 connector is given in Table 3.5 and Table 3.6, respectively. It is possible in a three-connection interface based on the cable's connection and the charger's position. In Figure 3.1: AC slow charging with separate charger shows the charger cable with converter and the EV without a charger. In this interface, the cable is detachable from EVSE and EV side.

In Figure 3.2, another interface connection with an on-board EV charger and simple detachable charging cable is shown. Figure 3.3 shows another connection scheme with an onboard charger and fixed cable at the EVSE end. This charging scheme does not have a requirement of communication because of non-controlled charging.

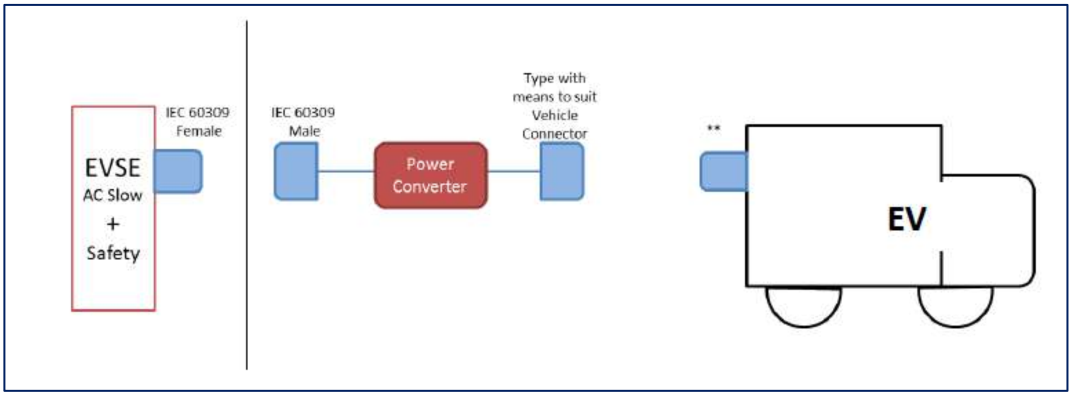


Figure 3.1: AC slow charging with separate charger (AIS, 2017)

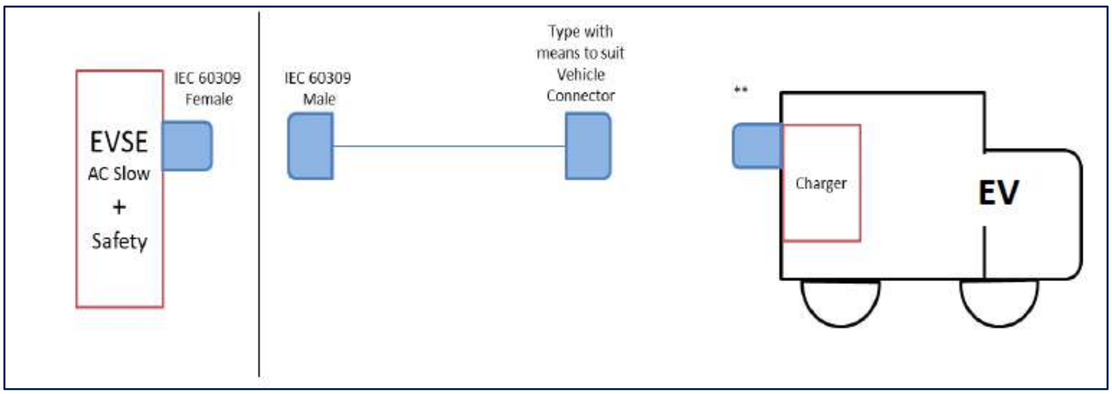


Figure 3.2: AC slow charging with On-board charger (AIS, 2017)

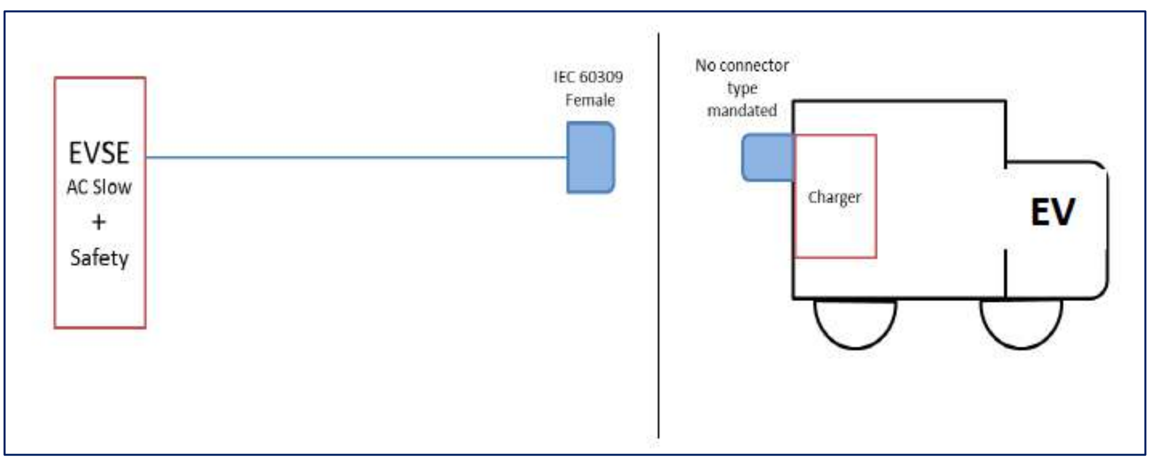


Figure 3.3: On-board charger with fixed cable (AIS, 2017)

3.2.1.2 AC fast charging mode

It is a three-phase AC charging system with a current rating of 63 A and IEC 62196 connectors shown in Figure 3.7. It is operating at 415 V with +/-10% tolerance. Pin information and nomenclature of the IEC 62196 connector is given in Table 3.5 and Table 3.7, respectively. This charging connector has control pilot functionality to control EVSE. This charging has the provision of communication to perform controlled charging using control pilot functionality. Two connection interfaces of AC fast charging with detachable and fixed cable from EVSE are shown in Figure 3.4 and Figure 3.5.

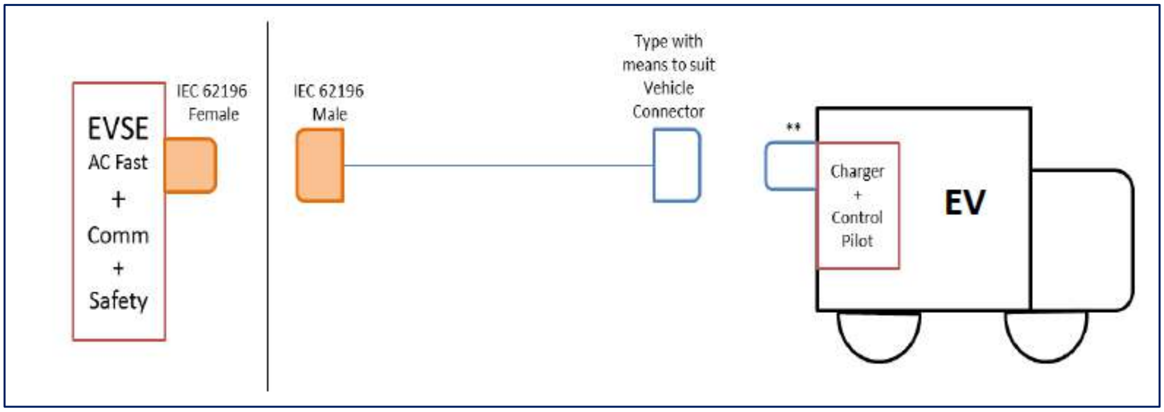


Figure 3.4: AC fast charging with free cable (AIS, 2017)

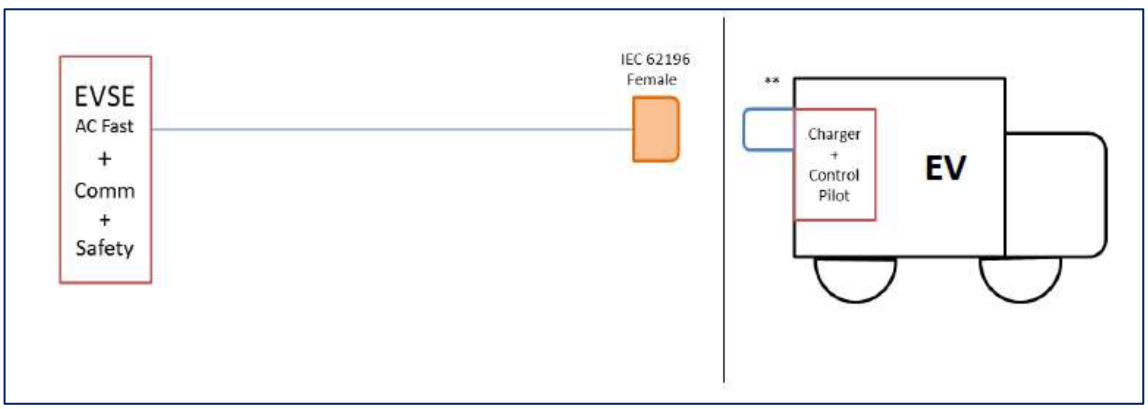


Figure 3.5: AC fast charging with fixed cable (AIS, 2017)

The standard provides the mandatory and additional safety functions for maintaining personnel and equipment safety by using a visual safety indicator. Mandatory and optional safety functions while AC conductive charging are given below.

Mandatory safety functions:

a. Earth presence detector should sense the earth connection between the AC socket and EVSE during the start of the charging session. It also senses the earth connection periodically through charging sessions.
b. Earth continuity checks the checking the earth connection between EV and EVSE throughout the charging session.
c. EVSE should have overvoltage and undervoltage protection.
d. It also has overcurrent and short circuit protection.
e. Leakage or fault current in EVSE should be detected and limit within 30A.
f. Connector locking should be adequately checked throughout the charging sessions. In AC slow charging, this is maintained by physical attribute.
g. EVSE should have protection against environmental conditions such as temperature, water, and solar irradiation.
h. It should have the ability to detect the phase and neutral interchange even if all mandatory safety functions are functional.

Optional safety functions:

a. It covers the checking and maintenance of the proper connection between EVSE and vehicle inlet. It should maintain the connection by making it impossible to move the vehicle by its own propulsion.
b. System should not energise until the control pilot function between EV and EVSE established adequately.
c. System should de-energise when the control pilot function is interrupted, but the control circuit can remain energised.
d. Power quality of the input supply needs to be continuously checked by monitoring rated power, voltage, and frequency tolerance for analysing possible faults, and corrective actions need to be taken.
e. Fail-safe handling operation should function for specific faults.
f. Determination of ventilation required for charging should be performed, and additional ventilation needs to be provided if required.
g. Means of determination and adjustment of available EVSE load current should be provided such that its charging rate does not exceed maximum current and power rating.
h. A mechanical mechanism should be provided to release and retain the coupler.

The standard mentions that for AC fast charging, pilot and proximity functions are mandatory. Requirements for protection against electric shock, direct contact and faults are also mentioned. Discharge of capacitor at different operating conditions are detailed from protection against direct fault. Standard mentions that the voltage between any conductive accessible part and earth should be lower than 42.4peak or 60V DC after one second of disconnection of EV from the supply. The stored energy, in this case, should be lower than 20J. If the value of voltage or energy goes beyond the limit value, then the warning label will be visible. The details mentioned above are also applied for the disconnection of EVSE.

Standard covers the electrical interface requirement between EV and EVSE.

Table 3.5: Pin information of IEC 60309 and IEC 62196

Sr. No.	IEC 60309	IEC 62196	Function
1	Single Phase, 15 A	Three Phase, 63 A	L1
2		Three Phase, 63 A	L2
3		Three Phase, 63 A	L3
4	Single Phase, 15 A	Three Phase, 63 A	Neutral
5	Rated for fault	Rated for Fault	PE
6			Control Pilot
7			Proximity

Charging cable requirements, EVSE requirement, IP address of EVSE, and constructional requirement of EVSE is given in standards. It also includes the dielectric withstand characteristics and tests for ensuring the normal operation of EVSE. It also provides a detailed understanding of pilot function through control pilot function using PWM modulation. Stepwise operation of control pilot function between EV and EVSE is presented. Detail connector information for AC slow and fast charging as provided in standard is given below.

Figure 3.6: Connector- IEC 60309

Table 3.6: Full form of connector pins in IEC 60309

Abbreviation	Full form
L	Line pins
N	Neutral
G	Ground

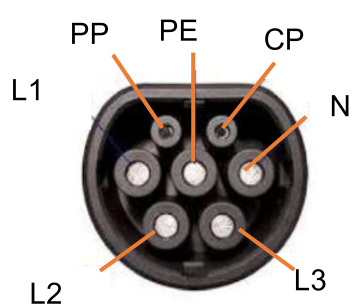


Figure 3.7: Connector- IEC 62196

Table 3.7: Full form of connector pins in IEC 62196

Abbreviation	Full form
L1, L2, L3	Line pins
N	Neutral
G	Ground
PE	Protective Earth
PP	Proximity Pin
CP	Control Pilot Pin

The IEC 60309 is a household connector with a line, neutral and ground. It is used for EVSE-AC slow. IEC 62196 type 2 has different pins for performing various tasks as controlling, protection, etc. It is used at EVSE-AC fast.

Different cable assemblies for AC slow and fast conductive charging are given in Table 3.8.

Table 3.8: Cable assemblies for AC slow and fast conductive charging

Cable Name	Description	EVSE Outlet
A	EVSE to Power Converter and Power Converter to EV	AC Slow
B	EVSE to EV	AC Slow
C	Attached to EVSE	AC Slow
D	EVSE to EV	AC Fast
E	Attached to EVSE	AC Fast
F	Extension Cable for D to connect to EV	AC Fast

EVSE categorisation based on maximum load capacity is given in Table 3.9. EVSE type should be selected before the actual installation based on charging requirements at the installation location. While selecting EVSE type, sanctioned load at the location should also take be taken into consideration.

Table 3.9: Types of EVSE

EVSE Class	Maximum Load
AC-Slow A	1 kW (1 Phase)
AC-Slow B	2.2 kW (1 Phase)
AC-Slow C	3.3 kW (1 Phase)
AC-Fast A	10 kW (3 Phase)
AC-Fast B*	12 kW (3 Phase)
AC-Fast C*	23 kW (3 Phase)
AC-Fast D*	45 kW (3 Phase)

* *These EVSE types require permission for installation from the electricity board.*

3.2.2 AIS 138 part 2: Electric vehicle conductive DC charging system

Standards provide specification, performance, safety, and communication of DC conductive charging system. It addresses the requirement for a DC EV conductive charging station for a supply voltage of up to 1000VAC and 1500V DC (AIS, 2018). It also provides a general requirement for control communication between EV and DC EVSE. Definition of components and phenomenon related to DC conductive charging is explained in detail. The functionality of the DC charging station is given below and divided as mandatory and optional functionality.

Mandatory functionality

a. Verification of vehicle's connectivity to EVSE
b. continuous checking of protective conductor
c. Energisation and de-energisation of system
d. DC power supply to electric vehicle
e. Measurement of parameters as current and voltage
f. Releasing, retaining, and locking of the coupler
g. Insulation testing before charging session start
h. Overvoltage protection at battery terminals
i. Short circuit test before charging
j. Control circuit supply checking
k. Protection from overvoltage
l. User-initiated plus emergency shutdown

Optional functionality of DC EVSE

a. Determine ventilation requirement of the charging system
b. Adjustment and detection of real-time available load current requirement of DC EVSE
c. Selection of optimal charging current
d. Indication of vehicle connector status

DC EVSE is categorise based on various aspects such as insulation between input and outputs system, control, supply type, environmental condition, and rating.

1. According to insulation between input and output of DC EVSE
    a. Isolated DC EVSE
        i. Basic insulation
        ii. Reinforced insulation
        iii. Double insulation
    b. Non-isolated DC EVSE
2. According to the control scheme

a. Regulated control for DC EVSE
    i. Controlled current control
    ii. Controlled voltage control
    iii. Both
b. Non-regulated control for DC EVSE

3. According to supply power
    a. DC EVSE supplied by AC mains supply
    b. DC EVSE supplied by DC mains supply
4. According to the nature of the establishment
    a. Indoor
    b. Outdoor
5. According to DC output voltage rating
    a. Up to 60V DC
    b. Above 60 V DC till 1500V DC
6. According to charge control communication
    a. Communication by digital message and analog signal
    b. Communication only by analog signal using dedicated power line or communication contact
7. According to operator
    a. Dedicated to one or more EVs
    b. Interoperability with any EV

The standard specifies protection against electric shocks and the corresponding IP degree to be observed by various EV charging entities. Various tests for ensuring normal operation, such as environmental tests and insulation tests explained in detail. In addition to the normal mode test, some protective tests like leakage touch current test, and impulse dielectric withstand test, etc., are given. Different test with test procedure compliance criteria is specified in detail. Controlled current charging and controlled voltage charging of DC EVSE is provided with attributes as current ripple, rate of charging current.

The charging states of DC EVSE, digital communication, and the charging control process are mentioned in Table 3.10 with information exchange for DC charging control.

Table 3.10: Charging states and communication information

Information	Explanation
Current request for CCC system	Exchanges requested current value by EV
Voltage request for CVC system	Exchanges requested voltage value by EV
Communication protocol	Exchanges information with software of charging station
Various test information	Exchanges test information before charging starts

The standard also provides the detailed stages and explanation of CAN bus communication in between EV and DC EVSE. In addition to the operation and control procedure of DC EVSE, fault protection interlock operation, communication, and safety measures are also detailed.

3.2.3 Plug, Socket, Connector:

3.2.3.1 IS 17017 part 2/ section 2

IS 17017 is for the EV conductive charging system, and part 2 specifies the plug, connector, socket, and vehicle inlet. Section 1 of the standard covers general requirements, whereas section 2 covers dimensional compatibility and interchangeability requirements for AC pin and contact tube accessories. It covers the requirement of the plug, socket, vehicle connector, and vehicle inlet for operating voltage up to 45 V and charging current up to 63A three-phase and 70A single-phase. It provides the design and construction dimensionality of the physical conductive interface between the EV and power supply. The connector described in the standards has seven power and signal pins with specific purposes. The standard specifies two types of connectors of rating 63A, 415V three-phase supply and 70A, 230V single-phase supply. The design of the connector covers the design of the plug socket, vehicle connector, vehicle inlet, plug packing room and vehicle connector packing room with detailed dimensions.

3.2.3.2 IS 17017 part 2/ section 3

Section 3 or IS 17017 part 2 specifies the dimensional compatibility and interchangeability requirement for DC pin and contact tube vehicle coupler. Two DC charger connector socket charger assembly of rating 600V 200A and 1000V 200A is provided with the complete set of dimensions and design of vehicle inlet, connector, and latch for different charger connector type.

3.2.4 Safety Standards

The AIS 138 part 1 and part 2 standard mentioned above provide safety and protection for EV, EVSE, and operating personnel.

3.2.4.1 Communication

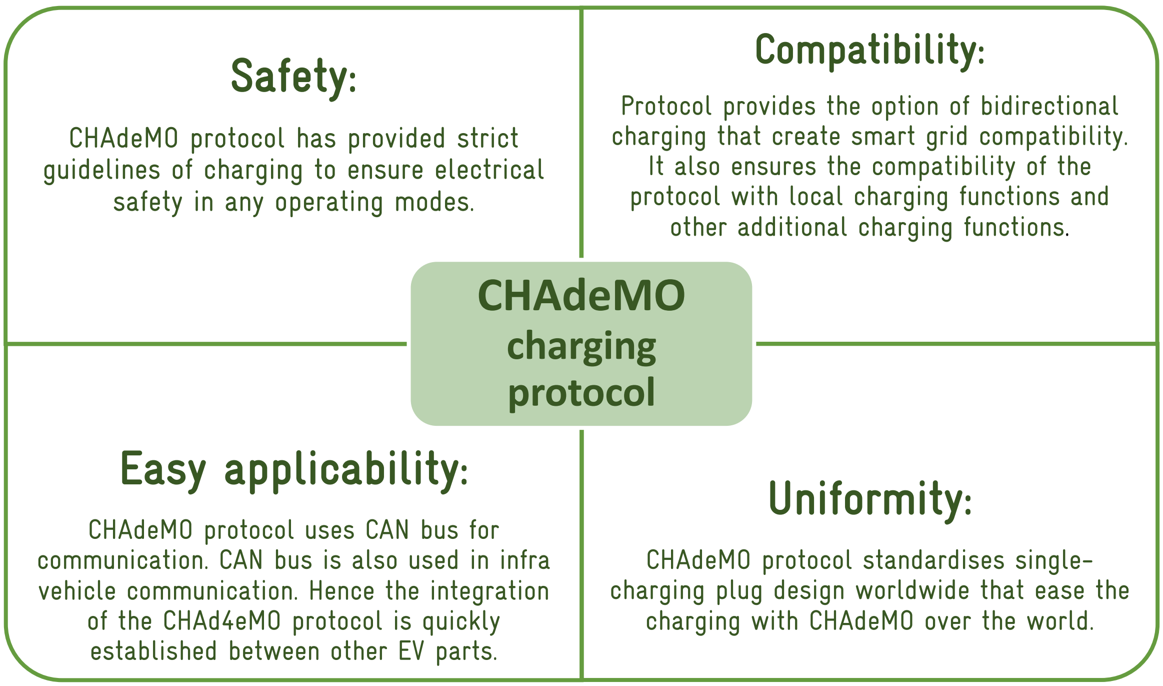
OCPP is the only open-source protocol used in India for communication between EV and EVSE in the EV charging system. Primarily OCPP 1.5 and above versions are used in India (OCA, n.d.).

Among the standards mentioned above, standards for charging station, plug, and connector govern the front-end EV ecosystem. Communication, energy transfer, safety, and power quality-related standards govern the back end of the EV ecosystem.

3.3 Charging protocols for EV charging

3.3.1 CHArge de MOve (CHAdeMO) Protocol:

CHArge de MOve (CHAdeMO) provides DC charging standards for EV that ensures seamless communication between charging point and vehicle. CHAdeMO charging protocol is applicable for 6 kW up to 400 kW. It is structured to feature safety, compatibility, easy applicability, and uniformity.



Technical specification of CHAdeMO protocol covers battery protection, safe charging control, electric shock protection, and connecter interlock. It is the first global DC fast charging protocol for EV that reduces range anxiety. The CHAdeMO Association is the responsible body for establishing and updating CHAdeMO protocols with varying market requirements.

CHAdeMO 0.9 was the first protocol providing basic charging features, and it was upgraded to CHAdeMO 1.0 in 2012 with additional features of protection and compatibility. In further years, smart charging by charging power modulation is introduced in the market. So, the older protocol version was upgraded to version 1.1 in 2015 with the functionality of dynamic current control. In 2017, modified protocol version 1.2 was released with the market-required features of high-power charging (200 kW), protection and coordination, and ground fault detection. Version 2.0, released in 2018, upgraded the high power charging capacity to 400 kW with the applicability of plug-and-charge (CHAdeMO, n.d.).

The latest protocol Chaoji is released in 2020 with a high power charging capacity of 900 kW (Kane, 2020). It provides backward compatibility with other global charging standards and a wide range of EV adaptability. This newer CHAdeMO protocol version is based on GB/T communication protocol using CAN bus communication and creates and supports harmonisation between CHAdeMO and GB/T (Blech, 2020). There are various country-centred charging standards applicable to EV charging in the market. To make EV charging a global service, harmonising these connectors and protocols is required, and Chaoji is the beginning of this standardisation.

The new Chaoji connector has an improved charging rate with a high charging current withstand capacity with comparatively smaller size. It is a liquid-cooled, lightweight, and compact DC fast charging connector (EVreporter, 2020). The compactness and lightweight structure are achieved because of the removal of the locking mechanism from the connector side. Key features of Chaoji are:

3.3.2 Tesla Charging Protocol:

Unlike other chargers, Tesla has its own proprietary charging protocol applicable only for charging their own EVs. It is not openly available for adaptation by others (Rajagopalan et al., 2013). The connector design of the Tesla supercharger is given in Figure 3.8 and Figure 3.9.

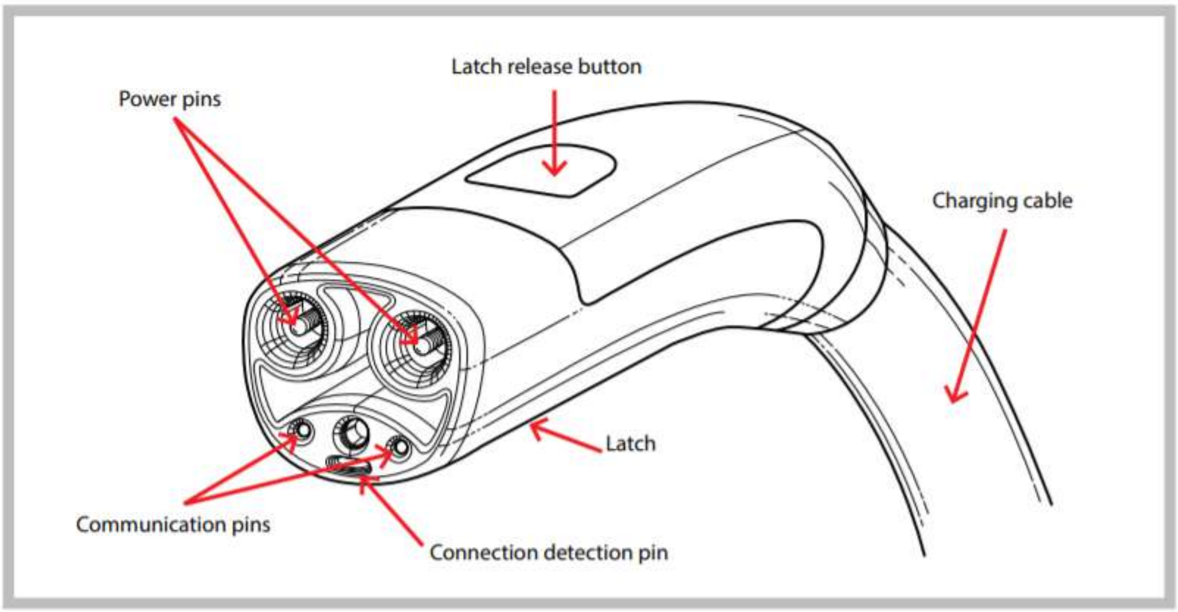


Figure 3.8: Diagram of Tesla supercharger connector

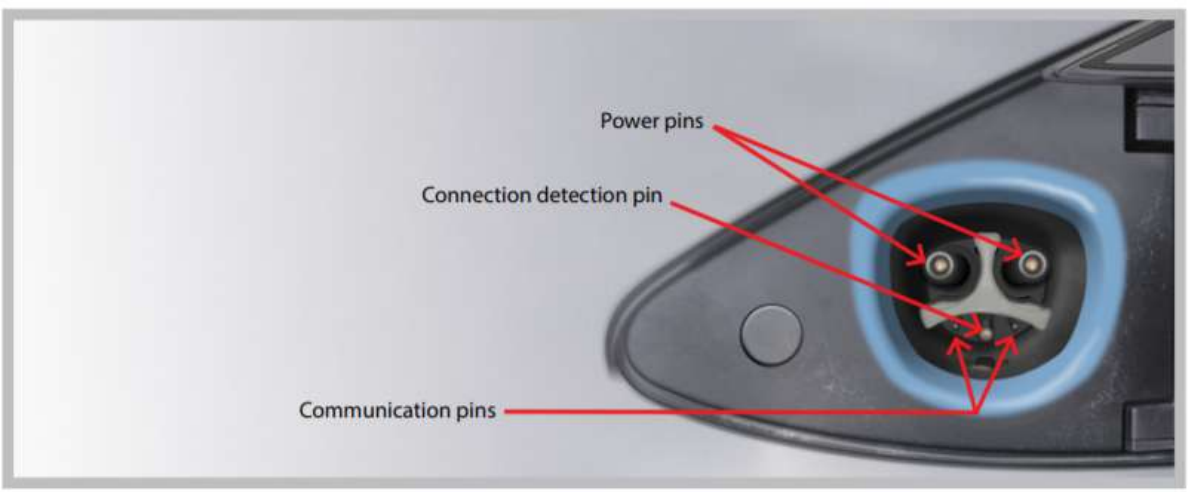


Figure 3.9: Connection pins in a practical supercharger

Tesla supercharger is applicable for AC and DC charging. Charging starts only after power and communication connection is established between the EV and charging point (Hydro-Québec, 2015).

3.3.3 Combined Charging System (CCS)

CCS is a charging standard developed by SAE and European Automobile Manufacturers Association. It is an upgraded version of type-1 and type-2 connector with two DC signal ports. It allows fast and AC/DC charging. Type1/SAE J1772 and Mennekes/type 2 plugs are modified by adding additional DC points to make the connector compatible with AC and DC charging. The type-2 connector is rated for a maximum of 63A current. The Combined

Charging System (CCS) is available in two design, CCS 1 and CCS2, as shown in Figure 3.10 and Figure 3.11. CCS1 is a combination of type 1/ SAE J1772 and DC ports, whereas CCS2 is a combination of Type2/Mennekes and DC port. These two CCS connectors follow SAE J1772, IEC 62196 protocols for charging purposes. These connectors are country-specific, which means that North America, Central America, Taiwan and Korea use the CCS1 connector whereas CCS2 is used in South America, Arabia, Australia and some other countries. It follows SAE J1772 signalling and communication protocol. CCS uses a Home plug Green PHY power line communication protocol (Kubel, 2015). Charging protocols defined by ISO/IEC 15118 is used for DC and AC charging communication. CCS charging is divided into seven layers starting from the physical layer to the application layer.

Figure 3.10: Connection pins in CCS1 connector

Figure 3.11: Connection pins in CCS2 connector

3.3.4 Type 2 AC charging

IEC type-2 connector is originated from a company called Mennekes, so the IEC type-2 connector is also called as Mennekes connector and is shown in Figure 3.12 (Mennekes, n.d.). IEC 62196 standard and relevant communication standard is used for Mennekes charging connector. The figure shown below gives the constructional design of the Mennekes connector.

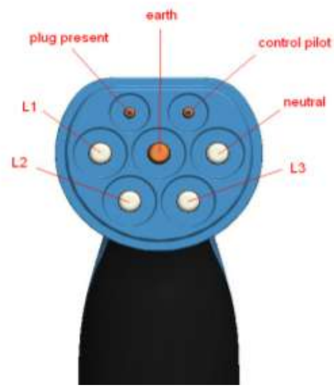


Figure 3.12: Mennekes connector (Type 2)

3.3.5 Bharat Charging Standards

Bharat charging standards are available for AC and DC charging. Bharat AC 001 and Bharat DC 001 are two Bharat charging standards. Bharat AC 001 supports AC charging with a maximum current rating of 15 A and 3.3kW (DHI, 2017). The IEC 60309 connector shown in Figure 3.6 is used in AC 001.

Figure 3.6 shows the IEC 60309 connector having N: neutral, L: line, and G: ground pins. This standard allows charging three vehicles simultaneously from a three-phase AC supply. This is low-power charging and hence specific communication standard between EV and EVSE is not specified in the standard. In contrast, communication between EVSE and the central management system is defined as OCPP 1.5 and higher versions.

Bharat DC standard DC 001 defined for a maximum rating of 200A and 15kW (DHI, 2017). The output voltage can be 48V/60V/72V as per battery configuration. Communication between EV and EVSE is done using GB/T protocol over CAN bus communication. OCPP 1.5 and higher versions are adapted for communication between EVSE and the central management system.

Both chargers should be constructed as per the design specification given in AIS Part 1.

3.4 Safety Standards of Electric Vehicle Charging Station

The safety standards cover the risk and safety components for equipment and the person assessing the charging station. The essential aspects of electrical safety are shown in Figure 3.13.

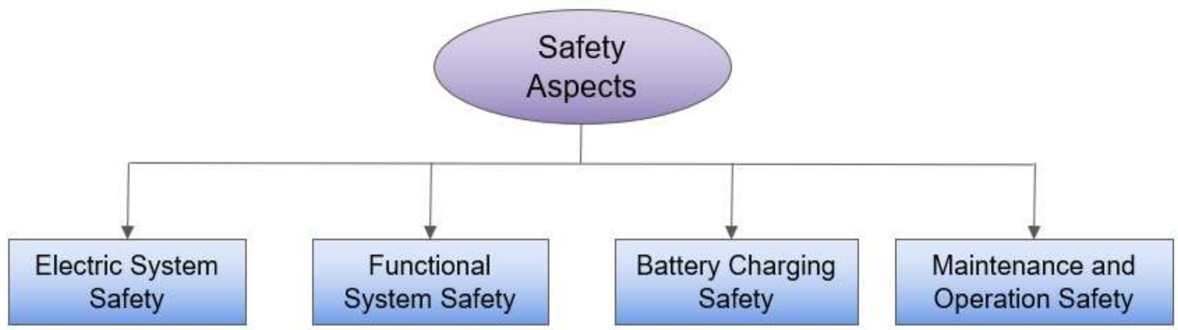


Figure 3.13: Safety aspect of charging station

Electric shock, fire hazards, injuries, insulation failure, charging coordination and electromagnetic compatibility are important points in safety standards.

Functional safety:

It includes the safety of a person from moving live part of the circuit and fire hazards. UL2202 and UL subject 2594 for the North American market state that the component that produces arc or spark should be 457mm above the floor (M.-H. Lu & Jen, 2012).

Individuals' safety:

To protect the persons from electric shocks while using EVSE should be minimized by following IEC standards that state that the device's leakage current should be lower than 30mA.

Insulation failure: To minimize the insulation failure risk, a proper class of insulation must be provided by considering voltage stress and pollution in the environment. There should be a safe distance between the two conductive materials such that they can withstand impulse voltage. This distance is fixed considering the RMS value of voltages.

Electromagnetic compatibility:

Safety standards should specify the protection against electrostatic discharge, electromagnetic disturbance, and voltage surges.

Charging control:

The control pilot pin carries the charging and discharging signal to the EV from EVSE. Continuously monitoring the signal on the control pilot pin is an important protection aspect while ensuring safety during charging and discharging. Maintaining safety +2% and -2% of tolerance is selected to provide safety during charging and discharging (M.-H. Lu & Jen, 2012).

For attaining all the above protection, the IEC 61851 standard maintains all the safety necessities of a charging station. The globally accepted safety standards for charging station available in IEC 61851 standard is given below (IEC, 2017):

a. IEC 61851-1: Part 1: General Requirements
b. IEC 61851-21: Part 21: Electric Vehicle Requirements for conductive connection to AC/DC supply
c. IEC 61851-22: Part 22: AC Electric Vehicle Charging Stations
d. IEC 61851-23: Part 23: DC Electric Vehicle Charging Stations
e. IEC 61851-24: Part 24: Digital connection between a DC EV Charging Station and an Electric Vehicle for control of DC Charging.

In addition to the above standards, the charging station should also follow NEFA 70E: a standard for electrical safety at the workplace.

The safety standards for Indian EVSE is given in AIS standards. AIS standards are divided into two parts, so it is divided into AC and DC EVSE safety mentioned in standards below:

(i) AIS 138 (Part 1): Electric Vehicle Conductive AC Charging System (AIS, 2017).
(ii) AIS 138 (Part 2): Electric Vehicle Conductive DC Charging System (AIS, 2018).

3.5 Tests for Various Standards

There are different tests needed to be performed while operating the charging station at normal operation. Various standards provide different tests for checking the EVSE at normal operating mode. Various test for EVSE is given below (AIS, 2017, 2018).

1. Leakage - touch current
    1.1 Damp heat test
2. Environmental test
    2.1 Climatic environmental test
    2.2 Dry test
    2.3 Damp heat cycle test
    2.4 Cold test
    2.5 Solar radiation test
    2.6 Saline mist
3. Mechanical environmental test
    3.1 Mechanical impact test
    3.2 Stability test
4. IP test
    4.1 Water or dust test
5. Electromagnetic environmental test

5.1 Immunity to EM disturbance
5.2 Immunity to electrostatic discharge
5.3 Emitted EM discharge

In addition to this conformity test, periodic test should be performed per year to check the mechanical and electrical deterioration of EVSE.

In DC EVSE, some additional test needs to be performed:

1. Insulation test
2. Short circuit test
3. Di-electric withstand voltage test
4. Touch current limit test

3.6 Standards for power transfer between EVs to the distribution grid

ISO 15118-20 standard (not published till the time of writing this report) govern the process of EV supply to the distribution grid. ISO 15118-20 offers twelve service features as stated below.

a. AC energy transfer
b. DC energy transfer
c. Wireless power transfer
d. AC automated connection devices
e. DC automated connection devices
f. Wireless power transfer with Automated connection devices
g. AC bidirectional power transfer
h. DC bidirectional power transfer
i. Wireless power transfer with bidirectional power transfer
j. AC Automated connection device with bidirectional power transfer
k. DC Automated connection device with bidirectional power transfer
l. Wireless power transfer automated connection device with bidirectional power transfer

This standard is yet to be released, and some features may change in the officially released document (V2G Clarity, 2019). ISO 15118 are the communication standards vehicle to grid (KPIT, n.d.).

Chapter 4: Communication in EV Ecosystem

For billing of EV users for their charging needs, for utilizing smart charging, and for provision of roaming facilities etc., communication among the different EV stakeholders is vital. These communications include communication between EV and EVSE, EVSE and CPO, CPO and CMS, CPO with DSO, etc. For each different communication layer different communication protocols have been developed, with each protocol having its own sets of functionalities. For example, there is a separate protocol that takes care of billing of the user based on the time the vehicle plugged in, the time the vehicle plugged out, the energy consumed, as well as the electricity tariff; similarly, there is a different communication protocol to enable demand response in EV charging. The different protocols for communication have been described in this section.

4.1 Communication Protocols in EV Ecosystem

Various open-source communication protocols for smart charging infrastructure are listed below:

4.1.1 OCPP

Open charge point protocol (OCPP) is a vendor-independent protocol and it introduces interoperability among charging equipment, software system provider (ElaadNL, n.d.). The protocol provides a communication link between the EV charging station and the central management system. It supports various topologies as charging station is directly connected to Charging Station Management System (CSMS) and Charging Station (CS) via local proxy, connection via local controller, non-OCPP connected to CS via OCPP, DSO control signal to CSMS. OCPP optimizes the cost and minimizes the communication infrastructure investment. It exchanges 'transaction event' containing the start of a transaction, the stop of a transaction, meters values, and status notification. OCPP 2.0 supports ISO 15118 with added features of plug and charge and smart charging (OCA, n.d.). It also has more interactive communication with users with high and secure authentication, choice of preferred language, and complete information of tariff cost and expected transaction cost.

4.1.2 OCPI

Open charge point interface (OCPI) provides a communication interface to exchange information about charge point between CPO and e-Mobility service provider (eMSP).

OCPI support various topologies as peer-to-peer, multiple peers with a different role, multiple peer-to-peer, and platform via hub. OCPI protocol is based on Hypertext Transfer Protocol (HTTP). Tariff signal from CPO is passed on to eMSP.

4.1.3 OpenADR

Open Automated demand response (OpenADR) enables the smart charging feature in EV environment (openADR Alliance, n.d.). It facilitates the open and interoperable demand response solution by communicating pricing signal, available capacity from DSO, and load demand from clients. The communication link connects DSO and the energy management system. Open ADR works on Zigbee and HAN network. Open Response Demand Server (ORDS) perform information exchange between customer and various demand response programs to facilitate demand response. As the price of electricity varies with the time of consumption, Energy Market Information Exchange (EMIX) provides a standard way to transfer necessary time and interval data using OASIS Web Service Calendar (WS-Calendar).

4.1.4 OSCP

Open smart charging protocol (OSCP) communicates predicted capacity of the network to supply the system whereas clients indicates their charge requirements to the central system. The communication link is established between the charge point operator, eMSP and the DSO. OSCP is used for smart charging by communicating capacity, managing the grid, and handling the capacity budget. Consumption Capacity (CC), Generation Capacity (GC), Fallback Consumption Capacity (FCC), Fallback Generation Capacity (FGC), Optimum (O) are the types of capacity forecast used in OSCP for providing a capacity forecast. Communication between different parties in OSCP starts with ‘Handshake’-HTTP-204. The protocol’s working is based on HTTP combined with JSON

4.1.5 OCHP

Open clearing house protocol (OCHP) provides billing and transactions information to focus on roaming features of EV (OCHP, 2020). Communication through OCHP happens in between the charging management system and the clearinghouse system. The protocol is intended to introduce a roaming service. It authorizes charging session, reservation, billing, and information of charging point.

4.1.6 OICP

Open intercharge protocol (OICP) provides the feature of reservation of booking of EVSE. OICP protocol communicates between EMSP and CPO through the Hubject platform, and It communicates with the Hubject B2B service platform. The communication between the Hubject platform follows Simple Object Access protocol SOAP 1.1. The timestamp is followed by ISO 8601:1988 standard and provides in YYYY-MM-DDYhh:mm:ssTZD format.

4.1.7 eMIP

E-mobility interoperation protocol (eMIP) provide roaming service by providing authorization, data clearinghouse features (Gireve, 2019). The protocol is developed by GIREVE and communicates in between CPO and clearinghouse. This interoperation platform (IoP) works on an HTTP server to have seamless communication with all participants.

4.1.8 IEC 61850-90-8

It is a technical report which models EV as a logical node in a system to integrate EV with other DER resource like wind, PV, etc. The data in the model can be used using standard messaging protocol IEC-61850. This allows the external control of the charge point for AC and DC charging.

4.1.9 IEC 61851-1

The standard provides four modes of EV charging. Mode 1 and 2 specifies the AC charging specifications as:

Mode 1: 1ph-250V, 3ph-480V, 16A,

Mode 2: 1ph-250V, 3ph-480V, 32A,

Mode 3 specifies the control pilot signal controlling the AC charging,

Mode 4 specifies the off-board charging and communication through CAN and power line communication.

4.1.10 IEEE 2030.5

It is an IP-based IEEE adoption of Smart Energy Application Profile 2.0 / SEP2 which provides smart grid solution via internet-connected devices. This standard is originated at Zigbee smart Energy Protocol V1 and became the IEEE standard in 2013. It provides load control, meter data exchange, exchanging tariff information, energy flow reservation, and management of DER functionalities.

4.1.11 IES/ISO 151

It is a high-level communication-based protocol. It specifies the essential requirements of network and application protocol, describes physical and data layers and physical and data layer requirements for wireless communication. It supports the authorization of charging, EV charging, smart charging, and reservation.

4.1.12 ISO/IEC 15118

It provides bidirectional communication between EV and the charging station to achieve plug and charge capability via power line communication. In the future, SoC and time of departure can be obtained from EV to have smart charging (ISO, 2019). It is provided by the collaborative work of ISO and IEC for providing general requirement and use cases for conductive and wireless high-level communication between EV and supply equipment. Additional roles of ISO/IEC 15118 series are, to provide network and application protocol requirements, physical and data link layer requirements for high level communication (HLC) between communication controller between EV and supply equipment (EVSE).

4.1.13 SAE J2847

It mentions the communication requirements between EV and the charging infrastructure. A detailed description of communication between EV and the utility, and between EV and off-board DC charger is provided. The communication will be established based on power line communication technology (Bohn, 2013). SAE J2847 provides the requirement and specifications for communication associated with energy transfer and other applications between EV and the utility grid. Specific roles of various sections in the ISO/IEC 2847 series are listed in Table 4.1.

Table 4.1: Section of SAE J2847

Standard	Role
SAE J2847/1	It provides a detailed understanding of the communication of EV for smart charging using smart energy profile 2.0
SAE J2847/2	It provides a detailed discussion on communication between EV and off-board DC charger
SAE J2847/3	It provides communication of EV equipped with onboard inverter and communication as a distributed energy resource
SAE J2847/6	It provides the requirements of communication for wireless energy transfer between light-duty EV and the charging station

The open-source protocols for EV smart environment have four major functionalities

i. Smart Charging

ii. Roaming
iii. Communication between the central system and charge point
iv. Communication between EV and charge point

For achieving the above-mentioned major functionalities of the EV smart environment, different protocols are implemented to address the same functionality. Various protocols for achieving the same functionality have some typical overlapping roles. The number of protocols for specific function with their roles are mentioned in Table 4.2, Table 4.3, and Table 4.5 (ElaadNL, n.d.).

Table 4.2: Smart charging protocols and the supported roles

Functionality	Smart Charging			
Protocol	OSCP	Open ADR	OCPI	IEEE 2030.5
Version	1.0	1.1	v0.4	2
Role within protocols				
Smart Charging	✓	✓	✓	✓
Roaming			✓	
Reservation of CP			✓	
Registration handling		✓		✓
Charge point information providing			✓	
Controls charge point				
Grid management	✓	✓		✓
Registration handling				
EV charging				
Billing and transactions				
Authorization of charging			✓	

Table 4.3: CS-CP and EV-CP protocols and the supported roles

Functionality	Central System- Charge Point (CS-CP)		EV- Charge Point (EV-CP)	
Protocol	OCPP	IEC 61850-90-8	IEC 61851	ISO 15118
Version	1.6	-	-	-
Role within protocols				
Smart Charging	✓		✓	✓
Roaming				
Reservation of CP	✓			✓
Registration handling				
Charge point information providing				
Controls charge point	✓	✓		
Grid management	✓	✓		
Registration handling				
EV charging			✓	✓
Billing and transactions	✓			

Authorization of charging	✓			✓

Summary of open communication protocols in the EV ecosystem is given in Table 4.4.

Table 4.4: Open protocols in the EV ecosystem

Sr.No	Name of the Protocol	Year of publication	Licensing agency	Communication between entities	Role and applicability
1	OCPP (Open charge point protocol)	2016	Open Charge Alliance	EV charging station and central management system	Provides interoperability among charging equipment, software system provider
2	OCPI (Open charge point interface)	2014	National Kennisplatform Laadinfrastructuur(NKL)	CPO and EMSP	Exchange information about charge point between CPO and EMSP
3	Open ADR (Open Automated demand response)	2015	Lawrence Berkeley National Laboratory and OASIS Energy Interoperation Technical Committee.	DSO and energy management system	Very important for Smart charging feature. Aims to develop an open and interoperable demand response solution.
4	OSCP (Open smart charging protocol)	2015	Open Charge Alliance	Charge point management system/EMSP and DSO	It communicates real time charge prediction capability and client's need
5	OCHP (Open clearing house protocol)	2016	Smartlab, ElaadNL	Charging management system and clearing house system	Information related to billing and transactions to provide roaming EV feature
6	OICP (Open Inter charge protocol)	2013-16	Hubject	EMSP and CPO through Hubject platform	Provides the feature of reservation/ booking of EVSE (roaming protocol)
7	eMIP (E-mobility interoperation protocol)	2016	GIREVE	CPO and clearing house, provided by GIREVE	Provide roaming of charging service by providing authorization, data clearing house. Access to charging point database

The detailed communication of the entire chain between EV and DSO is given in Figure 4.1 (ElaadNL, n.d.):

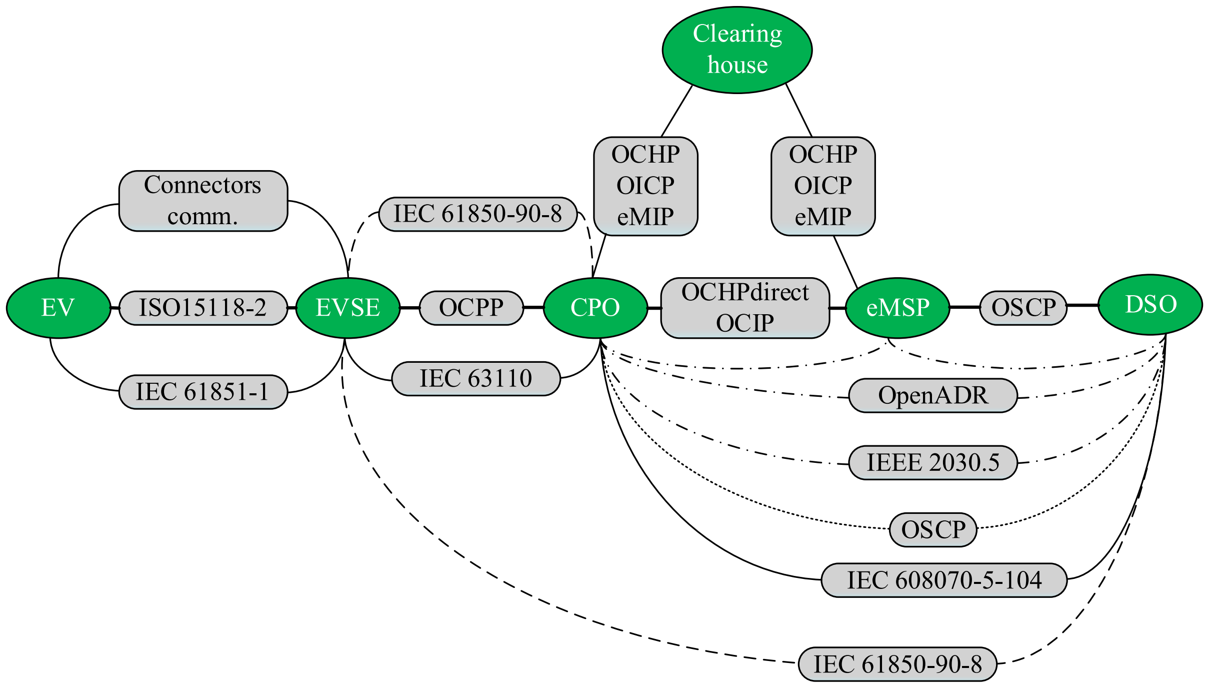


Figure 4.1: Communication links in EV ecosystem (ElaadNL, n.d.)

Integration of EV into distribution grid impacts the stability and voltage security of a grid. To protect the grid from instability, some inputs from the distribution operator are mandatory to perform smart charging. From the perspective of DSO, EV is a heavy load. This newly aggregated heavy load from the EVs can hamper the system stability and the grid reliability. So, the information of available capacity and system limits are necessary. This information from DSO can be passed to the charging operator, but if it is not correctly interpreted or ignored, it can lead to grid failure. So, to maintain the system stability, direct involvement of DSO is required.

The communication links between different charging participants with the specific standard and protocol used for communication are shown in Figure 1. The solid lines show the function-specific protocol, whereas the dotted lines show the generic protocols that can be adopted for different functionalities. Combinations of the different protocols are also used to achieve the smart environment.

Communication promotes the bidirectional charging, real-time data exchange, and the smart control environment. The protocols are flexible to adapt to any charging technology. The communication between EV and DSO is a combination of different operation-specific and open protocols.

4.2 Communication chain in EV Ecosystem

In this section, the sequence of communication between different participants in the EV ecosystem is comprehensively explained.

4.2.1 Communication between EV and EVSE

In this communication link, information of the EV model, manufacturing specifications, SoC level of the battery, maximum allowable current, and power ratings are communicated to EVSE using ISO 61851-1, ISO 15118-2, and connector communication. Connector communication mainly happens through CAN bus and PLC communication protocols. EVSE communicates the handshaking signal and controls the pilot signal on the pilot pin of the connector. This complete communication between EV and the EVSE starts the charging operation.

4.2.2 Communication between EVSE and CPO

Information collected from EV is then passed to the charge point operator to perform authentication and charging. In this communication link, EVSE passes the information of the EV model specifications for authentication check. It passes the technical specification as SoC level, DOD level of the battery, maximum allowable current limits, parking time, type of connector, and charging type. CPO also communicates the charging permission and charging power signal to EVSE.

OCPP is the most popular and majorly used open-source software between CPO and EVSE. IEC 61850-90-8 and IEC 61851-1 are the standards used for communication between EVSE and CPO.

4.2.3 CPO and eMobility service provider

In this link, CPO communicates various information, such as authentications requests of various vehicles, charging time-related information, charging point information (address, location, type), time interval, charge point status and availability, transaction and billing information, tariff, connector type, voltage, reservation details, and timestamp of the last update. This information exchange helps to authenticate the EV customer. It also helps with the bill processing. eMSP is also communicated on this link for directing the registered customer to the perspective CPO using the navigation system. eMSP also uses the communication link for transaction details and bill payment. The information mentioned above is about the direct connection between CPO and eMSP using OCHPdirect and OCIP communication protocols. There is another link between CPO and eMSP via a clearinghouse. The link of communication between CPO and clearinghouse is discussed below.

4.2.4 CPO and clearinghouse

CPO communicates tariff information, billing information, charging sessions information, and the charging time information to the clearinghouse. Clearinghouse verifies some of the information, such as authentication in real-time operation and billing at the clearinghouse platform. It sometimes communicates back the incorrect billing data to CPO. Clearinghouse is the same as the roaming hub platform described in roaming protocols. OCHP, OICP, and eMIP are the protocols used for communication between CPO and clearinghouse. These protocols are designed mainly for ease of billing and support the EV roaming.

4.2.5 Communication between clearinghouse and eMSP

Clearinghouse passes the billing data and charging sessions data to eMSP for communicating the payment information. This communication also uses OCHP, OICP, and eMIP.

4.2.6 Communication between eMSP and DSO

In this link, the e-mobility service provides real-time updates of energy required by the EVs for charging. This communication happens using the open smart charging protocol (OSCP). It provides the exact value of energy needed to be dispatched for charging load. eMSP also communicates the energy data and time corresponding to advance charging reservation. It predicts the charging load in the upcoming time interval so that DSO can react accordingly.

There is another protocol of communication between DSO and eMSP, and Open ADR. It performs demand response operations based on the load demand and the maximum available generation. The communication described above is the communication management chain between EV and DSO/DISCOM. It shows that a communication chain is the combination of various protocols with a specific purpose.

The communication protocols between the different entities have been enumerated below:

- Communication between EV and EVSE
    1. Connector communication (CAN bus, PLC communication)
    2. ISO 15118
    3. IEC 61851-1
- Communication between EVSE and CPO
    1. OCPP
    2. IEC 61850-90-8

    3. Open ADR and IEEE 2030.5
- Communication between CPO and eMSP
    1. OCHP direct
    2. OCPI
    3. OpenADR and IEEE 2030.5
- Information exchange between CPO and clearinghouse
    1. OCHP
    2. OICP
    3. eMIP
    4. OpenADR and IEEE 2030.5
- Communication between clearinghouse and eMSP
    1. OCHP
    2. OICP
    3. eMIP
- Communication between eMSP and DSO
    1. OSCP
    2. OpenADR
- Communication between EVSE and DSO
    1. IEC 61850-90-8
- Communication between CPO and DSO
    1. OSCP
    2. IEC 608070-5-104
    3. OpenADR and IEEE 2030.5

4.3 Communication Protocols applicable in India

Currently in India, Open Charge point protocol version 1.5 and above is primarily implemented for communication between EVSE and the charge point operator.

OCPP: Open charge point protocol (OCPP) is introduced by Open Charge Alliance in 2016. It is an independent protocol with interoperability among EVSE and software system provider. It is a communication link between the EVSE and the central controller. It supports various topologies as charging station directly connected to CSMS, CS and CSMS via local proxy, connection via local controller, non-OCPP connected to CS via OCPP, DSO control signal to CSMS. It exchanges billing data that contains the starting and ending of charging, energy meter data, and status information. OCPP 2.0 supports additional features of plug and charge and smart charging. It facilitates interactive communication with secure authentication and complete information of tariff and estimated charging bill. It provides compatibility between different EVSE operational in a charging station constructed by different manufacturers.

A wholistic view of standards utilized for EV charging has been presented in Figure 4.2.

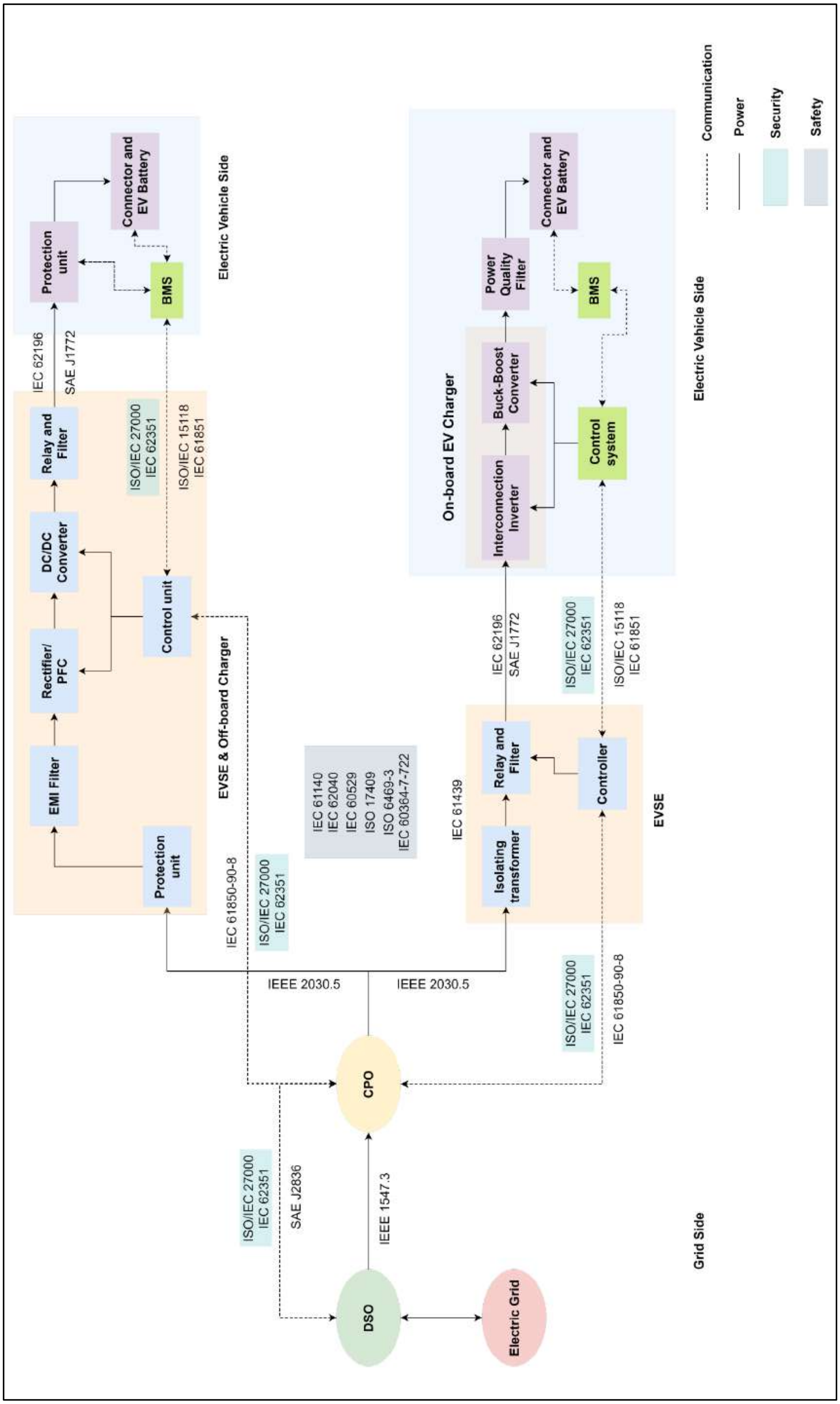


Figure 4.2: Standards for different aspects of EV charging

4.4 Global and Indian E-roaming Protocols

EV Interoperability is defined as the compatibility of entities within the EV charging environment to perform seamless charging operation. Seamless charging operation at any geographic location is achieved using roaming interoperability of the EV charging environment. Roaming is a service that allows the EV to charge at any charging station irrespective of the contracted mobility service provider. For achieving roaming for increased interoperability, roaming protocols with the desired functionalities are introduced globally. There are different roaming protocols practiced in different countries. Among all the available roaming protocols, four protocols namely Open clearing house protocol (OCHP), Open charge point interface protocol (OCPI), Open intercharge protocol (OICP), and E-Mobility interoperation protocol (eMIP) are majorly adopted for EV roaming and used primarily in Europe (Kam & Bekkers, 2020).

Charge point operators and mobility service providers are the actors responsible for the charging operation requested by the EV owner. Thus, the roaming protocols also revolve around the communication between the charge point operator and mobility service provider. The third entity, called a roaming hub, is introduced in roaming protocols to ease the information exchange and communication between these two actors. Based on the connection and presence of the entities of the EV roaming infrastructure, roaming connections are classified into two types, peer-peer connection and roaming hub connections. Out of the major four protocols, some allows single connection characteristic while OCHP allows connection for roaming. The brief information of these protocols with their role and applicability is given below.

4.4.1 Open Clearing House Protocol (OCHP)

Open Clearing House protocol (OCHP) is an open roaming protocol used to exchanging charging transaction data, authorization and charging station information between the charge point operator and the mobility service provider (OCHP, 2020). It is available in two variants, OCHP and OCHPdirect. Based on the connection between the entities, OCHP performs roaming through the clearinghouse platform, whereas OCHPdirect directly connects charging station operators and mobility service providers. eclearing.net is a clearing platform used for OCHP protocol. OCHP follows asynchronous communication. Contrary to real-time authentication verification, a list of authenticated users of respective MSP is uploaded on the roaming hub. This list is accessible to the CPO for the authentication of the EV. The asynchronous communication through a list of authenticated users avoids complete system failure issues in case of faults or maloperation of the roaming hub platform.

Role of involving entities in OCHP:

a. Charge point operator: It checks the authentication of the requested EV from the list of users provided by MSP through the roaming hub. It provides charging station access to the authenticated EV driver of contracted MSP and sends charging information to the roaming hub for bill processing. It gets paid for the charging session by MSP on behalf of its registered EV customer.
b. Mobility service provider: It provides a list of authenticated customers to the roaming hub for asynchronous authentication from CPO. It provides a seamless charging option to contracted the EV customer through a roaming hub connection with available CPO near to the EV customer. It pays the charging cost to CPO for its customers.
c. Navigation service provider: It provides the list of nearest charging stations with their location, route to the EV customer. It can have a contract with MSP or CPO.
d. Clearinghouse platform operator: It is also called a roaming hub. It acts as a middle actor to share and transfer the information between CPO and MSP to provide a seamless charging experience to the customers of the contracted mobility service providers.

Functionalities of OCHP:

a. Roaming through roaming hub platform: OCHP provides a roaming facility, hassle-free access to the nearest charging station irrespective of location and MSP of the charging station. eclearing.net is a clearing hub platform used in OCHP.
b. Authentication: OCHP facilitates authentication of requested EV customer by providing authenticated users list to CPO from MSP. Every EV customer has a specific ID allotted by MSP, and MSP uploads the list of customer IDs on the roaming hub platform. CPO accesses that list, checks the customer ID in it, and approves authentication.
c. Billing: CPO collects and sends charge detail records (CDR) to the roaming hub. The roaming hub checks the CDR and sends it further to MSP for payment to the CPO. If CDR is incorrect, then it sends it back to the CPO for corrections.
d. Provide charge point information: CPO provides charge point information to the roaming hub to further make it available for MSP to send to the EV users. OCHP indicates the customer's ID, charging point information (address, location, type), time

interval, charge point status and availability, transaction and billing information, tariff, connector type, voltage, reservation details, and timestamp the last update.

e. Provide real-time data access: It also provides real-time data to the MSP from CPO via the roaming hub. Real-time data covers the status and availability of the charge points. It constitutes available, reserved, occupied, out for maintenance data of charge points in the charging station.
f. Provide session data: It also provides CDR, starting and ending charging time, charging duration, point connector type, meter ID, and cost.
g. Remote access to charging point: It allows remote access to the charge point via mobile or web application of MSP.

Functionalities of OCHP direct:

a. Roaming: It provides a roaming facility via direct peer-peer connection in between CPO and MSP
b. Authentication, remote access: MSP application provides authentication functionality to CPO and remote control of charge point to EV customer.
c. Charging detail: It provides transaction details, tariff details, and charging session information.

4.4.2 Open Inter Charge Protocol (OICP)

OICP is a protocol for charging point information exchange between CPO and MSP via Hubject platform (Kam & Bekkers, 2020), (HUBJET, 2021). It is the most used roaming protocol in Europe. It allows an objective-based approach and real-time communication, as well as the possibility of asynchronous communication.

Roles of involved entity:

e-mobility service provider: It enters in contract with EV customers, CPO and a roaming hub, and in OICP where the roaming hub is Hubject platform (ElaadNL, n.d.).

Charge point operator: Hubject, the roaming hub platform, is connected to CPO aggregators. Many CPOs are connected to the protocol through the aggregator.

Hubject: It is a roaming hub in OCPI. It communicates between MSPs or CPOs to allow the EVs to charge at any CPO other than the contracted CPO of its MSP. It is connected to the roaming hub of MSP.

Functionalities of OICP:

Roaming: The customer management systems of MSP and the charge point management system of CPO are connected to Hubject B2B platform for exchanging the information between connected MSP to CPOs. Hubject B2B platform is a web service which was provided by Hubject in 2013.

Authorisation: It matches the EV ID provided by CPO and matches with MSP ID to complete the authentication. It stores the information and has backup data, but it does not support downloading from the server and performing real-time operations.

Reservation and billing: EV users can request the charging point within the charging station through MSP and Hubject contract connection. Hubject checks the type, compatibility of charge points with vehicles specification provided with MSP. After matching the compatibility, it sends a request to CPO for reservation. For billing purposes, CPO sends CDR of charging session to Hubject and is further redirected to the respective MSP for billing transactions.

Providing information: It provides static and real-time charging information to the contracted CPOs and MSPs. CPO provides charging point information, real-time and charging session information to Hubject. Hubject forwards the necessary information to the MSP for billing and transaction. The CPO provides the charging time, charging type, technical charging parameters, availability and status of the charging points, time intervals related to the charging sessions, and authentication IDs to the Hubject platform. In contrast, MSP provides customer authentication and EV specification information.

Remote access to charging station: Remote starting and stopping operation of the charge point is available with MSP application.

4.4.3 Open Charge Point Interface (OCPI)

It is a roaming protocol formed by Dutch CPOs and MSPs (Kam & Bekkers, 2020). It is a real-time protocol, but it also allows asynchronous communication. This protocol provides both the roaming options via the hub and peer-to-peer (Kam & Bekkers, 2020). It requires a version check for peer-to-peer information exchange in the absence of a hub. Smart charging can be performed using OCPI by adopting different OCPI smart charging options. The alive check option is also available with the hub platform.

Roles of different entities in OCPI:

Charge point operator: It provides charging station access to the authenticated EV customers. Information of charging session and charge point is provided for authentication and bill processing.

e-mobility service provider: It connects multiple CPOs through a roaming hub for easy charging of contracted customers. It also performs the role of the navigation service provider and the smart charging service provider in OCPI.

Functionalities of OCPI:

a. *Roaming:* It allows the roaming operation via an online platform hub or peer-to-peer connection. Roaming through the platform allows easy and promising communication and data exchange. Opposite to this, peer-to-peer establishes a direct connection and allows direct negotiation between CPO and MSP.
b. *Authentication and remote access*: OCPI works on tokens. MSP provides these tokens to CPO via the platform in real-time or by using a list of contracted customers with the token. It also facilitates remote start-and-stop permission via the MSP application
c. *Reservation and billing*: It allows reservation through the MSP app and sends bill in invoice format to the MSP.
d. *Provide information*: As mentioned in other protocols, it also shares static and real-time charging points and charging session data with CO and MSP.
e. Support to metered data: It allows access to signed meter data for smart charging and calibration.
f. *Smart charging*: OCPI allows the smart charging through different options such as: charge at cheapest, charge at fastest, use maximum renewable. This smart charging operation does not guarantee the desired charging within a limited time.

4.4.4 E-Mobility Inter Operation Protocol

e-Mobility Inter Operation Protocol is developed by GIREVE with an object to allow open access to all charging station (Gireve, 2019). It is mainly adopted in France (Kam & Bekkers, 2020). e-MIP uses GRIEVE platform as a roaming hub for coordinating in between CPO and MSP. It performs roaming via a hub and peer-to-peer, but the peer-to-peer connection is not used in practice. It allows real time and asynchronous operation for authentication.

Roles of various entities:

a. *E-mobility service provider*: It performs the basic functions of MSP, authentication, and billing. In addition to the basic functionalities, it allows car rental, car sharing, and navigation services to the EV customers.

b. *Charge point operator*: It provides charging information to the GIREVE platform. Data aggregator is another entity present in a system to collect and exchange the data of a particular area to the GIREVE platform.

c. *GIREVE hub platform*: It is a roaming hub in the eMIP protocol and performs coordination between CPO and MSP.

Functionalities:

a. *Roaming*: It allows roaming through the web-based GIREVE platform, and it is the same as roaming hub in other platforms.

a. *Authentication:* It allows authentication in two ways. In real-time authentication, CPO sends the authentication ID of the customer, and the hub platform checks and matches the customer authentication with MSP through an RFID card or MSP app. Asynchronous communication is performed using a list of authenticated users by MSP. In eMIP, CPO is not allowed to download the list of user's data, but it can request the hub to check the authentication.

b. *Reservation and billing*: Reservation of charge point is allowed through the MSP app. For bill processing, CDR is provided by CPO. Transaction details and CDR is downloadable via the GIREVE platform by MSP for billing payment.

c. *Provide information*: CPO provides real-time and static data on charging point and charging session on the GIREVE platform. It includes time interval related information, technical specification of the charge points and charging, and authentication and status information.

d. *Charge point finde*r: GIREVE allows charge point searching functionality. It facilitates MSP to search the charging points and their information in a particular area.

e. *Platform alive check*: GRIEVE platform send heartbeat signals to check the connectivity of CPO, MSP and data aggregator. This monitoring facility improves communication and data exchange and charging request processing. Table 4.5 summarises the roles of different roaming protocols (ElaadNL, n.d.).

Table 4.5: Roles of e-roaming protocol

Functionality	Roaming			
Protocol	OCHP	OCPI	OICP	eMIP
Version	1.4	2.1	2.1	0.7.4
Developing organisation	Smartlab Innovationsgesellschaft GmbH and ElaadNL	eViolin	Hubject	GIREVE
Role within protocols				
Smart Charging		✓		
Roaming	✓	✓	✓	✓
Reservation of Charge point	✓	✓	✓	
Registration handling				
Charge point information providing	✓	✓	✓	✓
Controls charge point				
Grid management				
Registration handling		✓		
EV charging				
Billing and transactions	✓	✓	✓	✓
Authorisation of charging	✓	✓	✓	✓

Table 4.6 provides information of roaming standards adopted in different countries.

Table 4.6: e-roaming protocols adopted in different countries

	OCHP	OCPI	OICP	eMIP	Other
Country					
France	✓		✓	✓	
Netherlands		✓			
Germany	✓	✓	✓	✓	
Portugal		✓			
Inter Europe					NeMo protocol
Austria			✓		
Canada		✓			
United States		✓	✓		

EV roaming is not yet implemented in the Indian EV environment. With increased EV adoption, EV roaming protocol's requirement will increase to facilitate charging of an EV with any charging station irrespective of whether contracted MSP has a direct contract with CPOs.

4.5 Information Flow for Communication between EV and DISCOM

The flow of information passing from EV to DSO is shown in Figure 4.3. It is a cyclic process to perform real-time charging at every time instances.

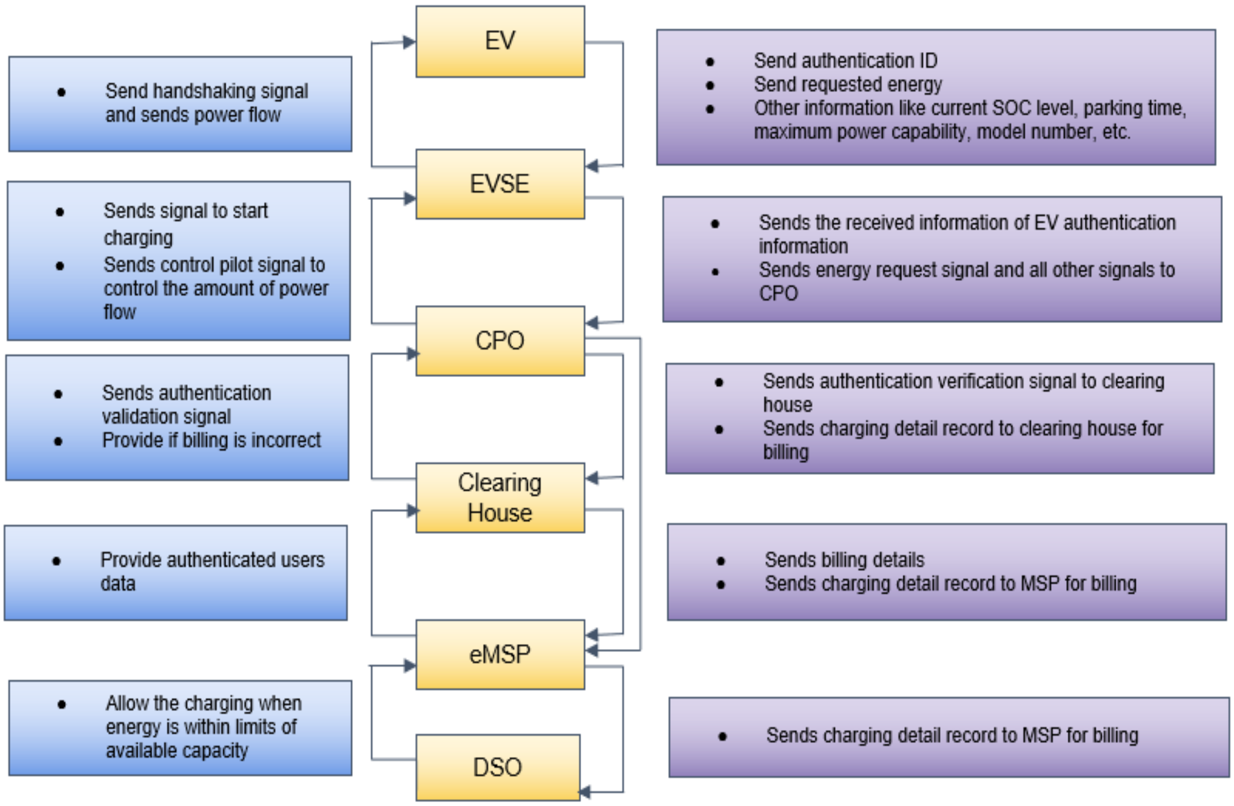


Figure 4.3: Information flow between EV environment

For initiating the charging between EV and the EVSE, several steps of connections are followed for EVSE to regulate the voltage of the control pin. The detailed signal flow and charging operation staring process is given in Figure 4.4.

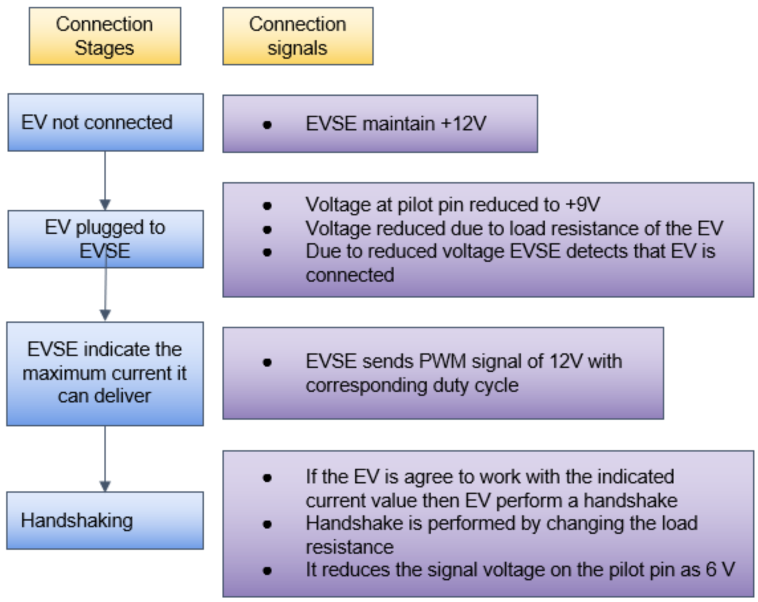


Figure 4.4: Communication between EV and EVSE

The duty cycle mentioned in step three of the above figure is elaborated here, such that the EVSE sends the duty cycle in proportion to the available current from the main supply (AIS, 2017). Interpretation of duty signal by EV and deciding duty signal by EVSE considering available current is given in

Table 4.7 and Table 4.8, respectively.

Table 4.7: Current signal in terms of duty cycle provided by EVSE

Available current	Duty cycle provided by EVSE
0	0 (EVSE not available)/100(No current available)
6<=I<=51	I/0.6A [10<=duty<=85]
51<=I<=80	(I/2.5A) +64[85<=duty<=96]

When EVSE sends a signal to the EV, at that time, EV also has a specific interpretation of the duty cycle (AIS, 2017).

Table 4.8: Current signal interpretation from duty cycle provided by EVSE

Control pilot duty cycle (%) interpreted by vehicle	Maximum current to be drawn by vehicle(A)
<3	0(charging not allowed)
3<=duty<=7	Indicates that charging is not allowed; digital communication can be used to control the off-board charger.
7<=duty<=8	0 (charging not allowed)
8<=duty<=10	6
10<=duty<=85	Duty (%) x 0.6
85<=duty<=96	(Duty-64) * 2.5
96<=duty<=97	80
97<= duty<=100	0 (charging not allowed)

4.6 Data security and safety standards

Data security can be defined as the set of standards and technology regulations that safeguard the data from any kind of modification, alteration, and destruction. To ensure security, cybersecurity standards must be maintained by following a few rules and regulations with a proper set of instructions to be executed. Since data security is essential for protecting privacy breaches and confidentiality, a proper guideline is to be followed while dealing with the datasets to achieve the security standard goal in improving the information and technology security. ISO (International Organization for Standardization) provides a set of standards to be followed for different types of products, such as goods, technology, services, quality, and safety. ISO 27000 series is the standard for regulating the framework security management services for information (Irwin, 2020).

- ISO 27000: This standard gives the detailed meaning of the terminologies used in ISO 27001.
- ISO 27001: This standard helps the stakeholders to check whether the best practice is implemented to secure confidential information data. This standard also provides the process orientation of steps while dealing with data sets.

- ISO 27002: These standards provide the standard operating procedure (SOP) to manage security standards practice considering the risk in handling the information by the following SOP to select information and control the information security.
- ISO 27032: This standard is an international standard, particularly for cybersecurity. These include the standard operating procedures for safeguarding the information beyond the borders of institutions, groups, partners, or others. It also has standards for sharing among different groups.

Chapter 5: Interoperability

Interoperability of Electric vehicle charging infrastructure and Electric vehicles refers to the compatibility of the grid, charging network, charging station, and EV, which are vital components of charging infrastructure with the supporting software system that allows all the components to work effectively and seamlessly (EPRI, 2019).

Benefits of interoperability (NESCAUM, 2020)**:**

- Simplifies billing and payment for the EV owner.
- Maximizes the access to the EV charging station for the EV owner.
- Promotes effective V2G communication for demand response and smart charging.
- Avoids the EVSE owner getting locked into a single network.

Electric Vehicles in different regions have different sockets due to manufacturing standards. All the internationally available charging connectors and the EV charging socket they are compatible with are represented in Table 5.1. All the charging connectors except Type 1 and Type 2 are only compatible with specific EV charging sockets. CCS charging is compatible with Type 1, Type 2, and CCS connectors. For interoperability between EV and EVSE, ISO 15118 should be integrated with EVSE and EV. It will allow the EVSE and EV owners to check the compatibility between the EV socket and charging connector and will enable the communication between the EV and EVSE to ensure safety by locking the charging connector and monitoring the charging session with BMS data exchange (EPRI, 2019; NESCAUM, 2020).

Table 5.1: Interoperability among different connectors

			Electric Vehicle Socket					
		Bharat AC 001	Type 1	Type 2	CCS	CHAdeMO	GB/T (Bharat DC 001)	Tesla supercharger
EVSE connector	Bharat AC 001	✓						
	Type 1		✓		✓			
	Type 2			✓	✓			
	CCS (DC)				✓			
	CHAdeMO					✓		
	GB/T (Bharat DC 001)						✓	
	Tesla supercharger							✓

5.1 Role of the standard

Standardization would enable both consumers and the system to function fluidly and efficiently. Currently, in the USA, several different plug adapters are being used. Nissan and Mitsubishi use the CHAdeMO connector, while Asian and all American and European manufacturers use the SAE CCS and Tesla has its own proprietary plug. This hinders interoperability. Issues with conflicting standards and approaches still exist and they include charger to network communication, vehicle to charger communication, open access and payment, and network to network communication (MJB&A, 2019; NESCAUM, 2020).

5.2 Open Access and Payment

Ability to pay and use any charging station without requiring any special membership or account will immensely increase the interoperability from the consumer side. For example, in the Netherlands, a single RFID card is used for all public charging stations (MJB&A, 2019; NESCAUM, 2020).

The Data Communication protocols/standards with Electric Vehicle Communication Controller (EVCC) and Supply Equipment Communication Controller (SECC) need to be installed in the EV charging infrastructure for effective and seamless interoperability (MJB&A, 2019).

5.3 e-Roaming

e-roaming is one of the key enablers that have widened the availability of charging infrastructure. The cooperation among the different charging service providers enables their users to access charging stations owned and operated by other charging service providers. Without an e-roaming facility, an EV user is boxed in to only charge his vehicles in those charging stations to which he is registered. They are restricted from charging their EVs in charging stations to which they have not registered. An e-roaming network opens up access to thousands of charging stations in the geographic area for an EV user. However, for the provision of e-roaming, there is a complex network of communication and contracts. There are two main ways to facilitate roaming services, as shown in Figure 5.1,

- Peer-to-peer roaming
- Roaming via platform

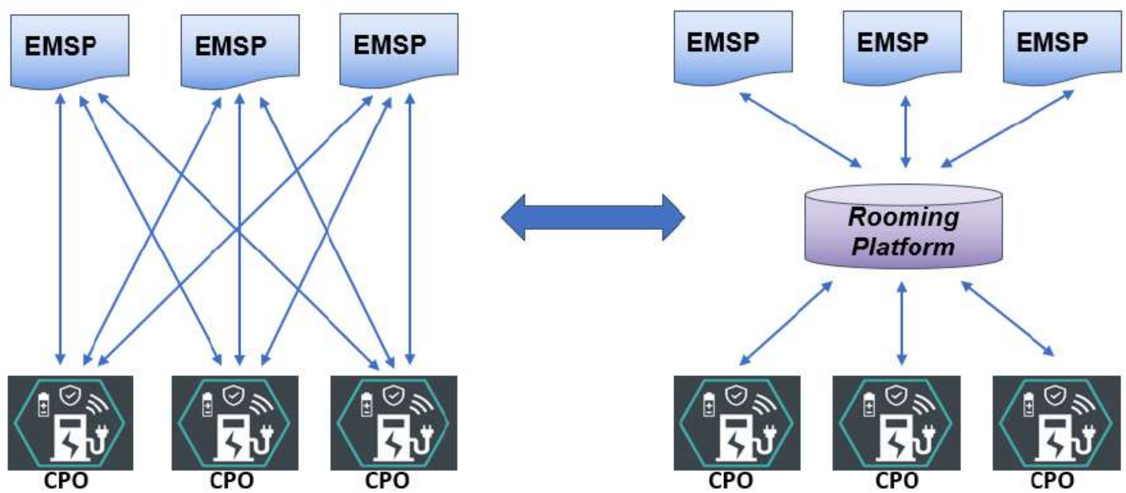


Figure 5.1: Peer-to-peer roaming (left) and roaming via platform (right)

In peer-to-peer roaming, eMSPs and CPOs have contracts between themselves, and the EV user registered to the eMSP has access to all the CPOs that have a contract with the eMSP as shown in Figure 5.2. Here, the EV user is registered with Mobility service provider 1, who has contracts with Charge point operator 4 and Charge point operator 5. This enables the EV user to charge in charging stations operated by either of the two charge point operators. Charge point operator 6 and Charge point operator 7 are however inaccessible to the EV user.

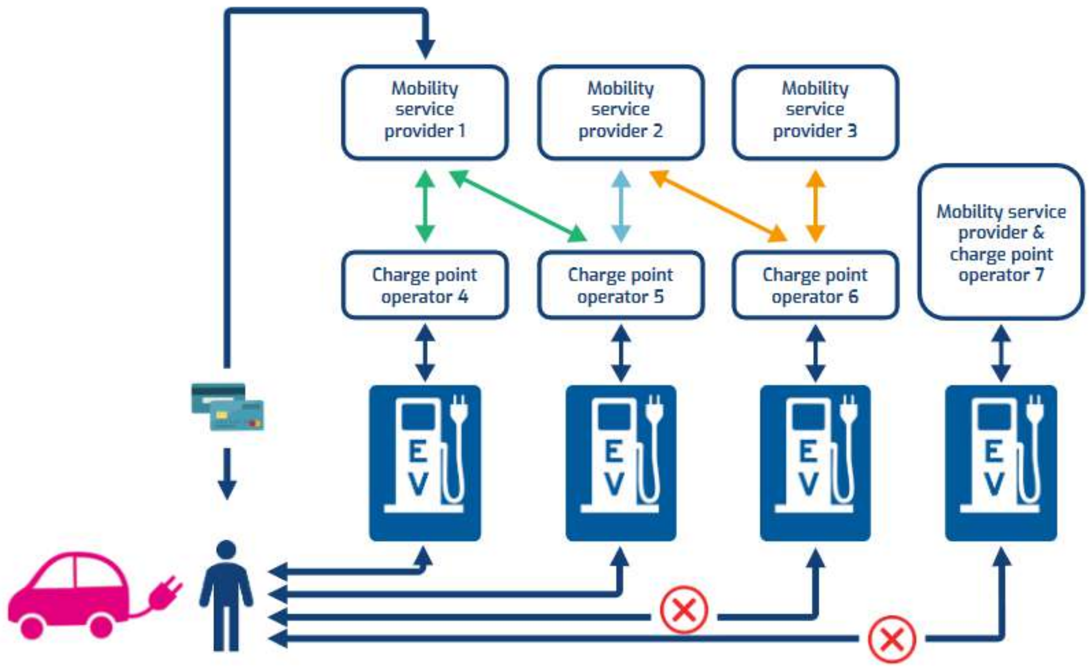


Figure 5.2: e-Roaming using peer-to-peer connections (Kam & Bekkers, 2020)

Comparatively, by connecting to a roaming hub, the eMSPs and CPOs get the advantage of immediate access to an extensive network, as shown in Figure 5.3. Here, the Mobility service provider 1 is connected to Roaming hub Aa which has connections with Charge point operators 4, 5 and 6. This enable the EV user access to all three charge point operators.

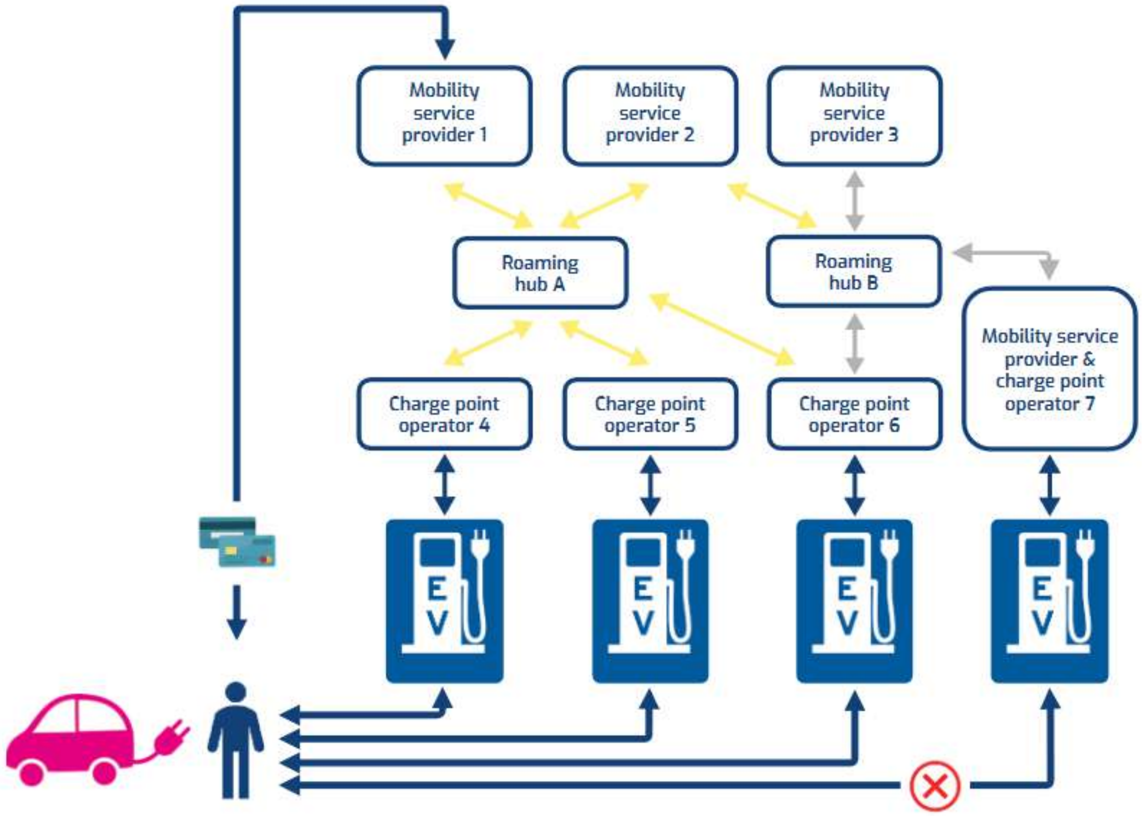


Figure 5.3: E-Roaming using roaming hubs (Kam & Bekkers, 2020)

Chapter 6: Grid Integration of EVs and its Impacts

Integration of electric vehicles (EV) with the grid is essential for acceleration of EV adoption in India. Increase in EV penetration will inevitably demand an increase in the number of EV charging stations. On the power sector front, India is striving to be an energy surplus nation, given that there was a peak power deficit of 0.8% in 2018-19. E-mobility is a deep confluence between the transport and power sector and therefore integration of EV charging infrastructure with distribution grids creates both challenges and opportunities for the conventional power sector. The key challenges faced in integrating EV charging infrastructure with the grid are explained in the below sections.

6.1 Voltage Stability Issues

Distribution network, generally due to the high resistance to inductance (R/X) ratios of the distribution lines, are more susceptible to voltage sags due to high power drawn which may even surpass the stable voltage operating zones. As EV charging entail a higher power demand compared to other residential loads, high penetration of EV will significantly increase the power demand in low voltage grids, which can potentially lead to voltage stability issues. In addition to this, EV charging may coincide with other loads in the system, as the EV users are likely to charge their vehicles in the evening period when they return to the premises. This coincidence between EV charging period with the peak demand period may further aggravate the voltage stability issue.

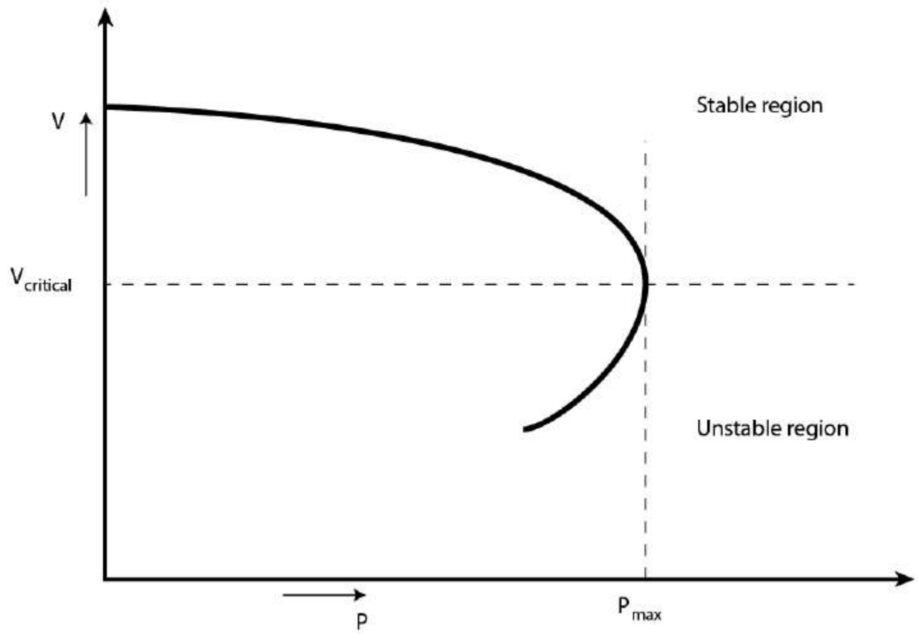


Figure 6.1: Typical power vs voltage curve **(Deb et al., 2018)**

The relation between active power and voltage of a bus is represented by the PV curve as given in Figure 6.1. It signifies the trend of voltage change with increasing active power. Based on the line resistance and reactance, each bus has a critical voltage which corresponds to the maximum active power that can be drawn from the bus, and any further increase in load at the bus will lead to voltage collapse. The ratio of change in voltage due to change in active power is termed as Voltage Sensitivity Factor (VSF) (Deb et al., 2018). A high VSF means that even for small changes in active power there is a large drop in voltage and vice versa.

6.2 Phase Imbalance

Unique to India, the 2W and 3W electric vehicle sector has seen a massive growth and is expected to dominate the national sales. However, these 2W and 3W are generally charged using single phase chargers. If these chargers are not uniformly distributed among the phases of the distribution network, it may lead to unbalanced phase voltages and current loading. Unbalanced operation of the network results in higher losses in the network, voltage issues and is detrimental to overall system health. For example, if power demand in one phase is higher than the other two phases, there will be voltage drop in the phase with high demand, while potentially leading to overvoltage in other two phases, due to shifting of the neutral point in a three phase four wire distribution system (Weckx & Driesen, 2015).

6.3 Increase in Peak Load

Uncontrolled EV charging could increase the peak load on the grid if the time of charging of the vehicles coincides with the existing load peak. This could contribute to overloading of the transmission system, distribution network assets like transformers and cables etc. This extra load would also lead to increase in generation and thus increase the electricity price (Klettke & Mose, 2018). It could also stress the system with increased requirement of ramp limits

6.4 Overloading

As mentioned above, the coincidence of EV charging with the network peak load, may further stress the system. This increased EV load can cause overloading in different assets of the distribution network, such as distribution transformers, cables, fuses etc. This overloading can significantly reduce the lifespan of the equipment, while simultaneously reducing the efficiency of energy transmission.

6.5 Power Losses

Power losses in the distribution network generally refers to the I^2R losses of the overhead lines/underground cables. Therefore, total power loss in the system is given by

$$P_t = \sum P_i = \sum I_i^2 R_i$$

Where, P_i is the loss of each line, I_i is the current flowing through each line and R_i is the resistance of each line. So, with added current flowing through the lines due to the extra EV charging load, the loss in the system also increases making the supply of power less efficient. Besides, unbalanced loading can lead to uneven losses among the three phases.

6.6 Power Quality

EV chargers, which are basically AC/DC and DC/DC converters are power electronic converter-based devices. These power electronic devices act as a non-linear loads in the system and introduce voltage and current harmonic distortions into the supply. The level of distortion is proportional to the number of EV chargers operating simultaneously in the distribution network.

The EV chargers also bring voltage excursions which the end use customers can detect as flickers in their lighting devices or change in speeds in the electrical motors.

The amplitude (or rms) value of a particular harmonic I_n can be defined in relation to the fundamental I_1 or the rms value I_{rms} as

$$i_n(\%) = \frac{100 I_n}{I_1},\ i_n(\%) = 100.\frac{I_n}{I_{rms}}$$

The total harmonic distortion (THD) is defined as the ratio between rms value of all the harmonics to the rms value of the fundamental component and can be expressed as

$$THD_i(\%) = \sqrt{\sum_{n=2}^{N}\left(\frac{I_n}{I_1}\right)^2} \times 100\%$$

6.6.1 Conductor losses

In presence of harmonic content, the added current flow increases the cable losses in the network. The current due to harmonic can be expressed as

$$I_{rms} = I_1\sqrt{1 + THD_i^2}$$

So the added losses due to harmonic content is increased due to I^2R losses as shown in Figure 6.2. This increased current leads to increase in conductor losses.

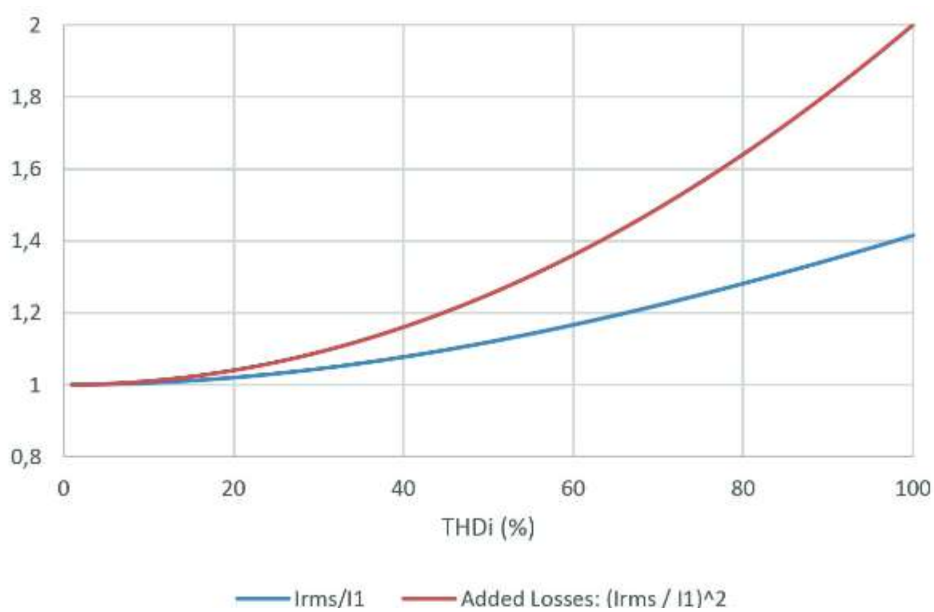


Figure 6.2: Illustrative example of increase in conductor losses with increased harmonic content **(Pinyol, 2015)**. The blue line represents increase in current due to harmonics and the red line represents the corresponding increase in cable losses in per unit values considering the current and cable losses with no harmonic content as base.

6.6.2 Neutral Conductor

Harmonics can be categorized into *positive sequence harmonics*, *negative sequence harmonics* and *zero sequence harmonics* based on their order.

The (3rd, 6th, 9th …) order harmonics are called zero sequence harmonics and also known as Triplen harmonics. These harmonics are in phase with the fundamental and circulate between phases and neutral as shown in Figure 6.3. Due to this reason, the presence of these harmonics increases the size requirement of the neutral conductor compared to the phase conductors, so that the neutral can carry out this extra current.

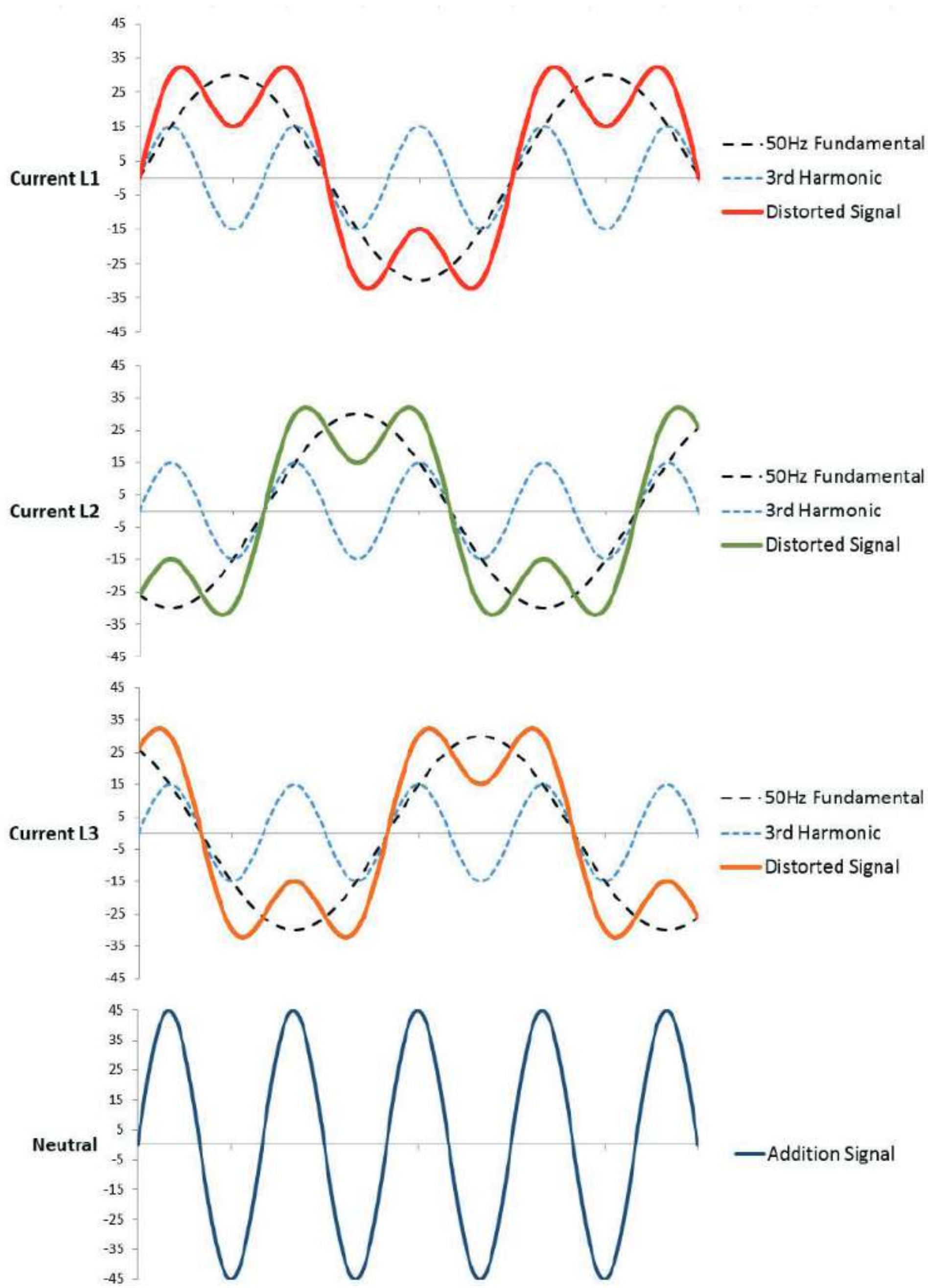


Figure 6.3: Effects of Triplen Harmonics on the neutral conductor **(Pinyol, 2015)**

6.6.3 Motors and Generators

The generators and motors are also affected by the harmonics in terms of efficiency reduction, overheating and derating. The increase in the eddy current and hysteresis loss due these harmonics results in increased core losses. Simultaneously, the copper loss, which is proportional to the square of current, also increases with increased harmonic content. Additionally, the negative sequence harmonics have the effect of force against torque rotation causing motor vibration, added heat generation, need for derating etc.

6.6.4 Transformers

Similar to motors and generators, transformers also face the same effects of increased core and copper losses. The presence of triplen harmonics can also heat up the neutral conductor in delta-wye distribution transformers. There is also the potential risk of resonance between the transformer inductance and supplied capacitive loads, at the harmonic frequencies. Additionally, there is noticeable noise and heat generation in laminated transformer cores at certain harmonic frequencies.

Moreover, two close conductors carrying alternating current in the same direction causes more magnetic flux in the area between the conductors, thereby leading to uneven current distribution known as the Proximity Effect. This effect, similar to Skin Effect is proportional to frequency, so for higher order harmonics the AC resistance of winding conductors will be further increased which results in added losses.

6.6.5 Circuit Breakers and Fuses

The thermal-magnetic tripping mechanism in circuit breakers responds proportionally to the rms current. Therefore, a distorted current signal, which has I_{rms} much higher than the fundamental I_1 can cause undesired tripping. Also, CBs that are designed to operate at zero current crossover points, can trip in the case of very distorted current with several zero crossovers within the fundamental period.

Similarly, for fuses, the rating of the fuse needs to be designed based on the rms current. So current with high rms values can cause the fuse to blow out.

6.6.6 Flicker

Harmonics in the network supplying power to lighting circuits can cause fluctuations of light intensity, visible to the human eye. This phenomenon mainly affects fluorescent and incandescent lamps.

Since the transformer forms the backbone of the distribution network so the impact of harmonics on the life of transformers will be explained in detail.

6.7 Impact on Reliability

From the point of view of the power system, EV charging changes the load pattern and consequently the generation needs, which affects the efficiency and the security of supply. The additional demand is highly stochastic and is dependent on a myriad of different factors such as EV user travel behaviour, charging time preference, charging power required, time of charging etc. The same EV user and EV can one day charge at fast DC chargers with power >50kW, and the next day charge at slow AC charger <10kW. This variability of power needs, stresses the requirement of energy generation. Further, if the distribution network is not designed to handle the added load, then the failure rate of the distribution network assets may increase hence reducing the reliability of the power supply. In a distribution network the reliability of the supply is closely related to the satisfaction of the end use customers. As such, the customer-oriented reliability indices are SAIFI, SAIDI and CAIDI, for which the statistical data of failure rate, repair rate, average outage duration and the number of consumers of the load points are required. The energy-oriented reliability indices are ENS and AENS.

The primary reliability indices used are given categorized as per Figure 6.4.

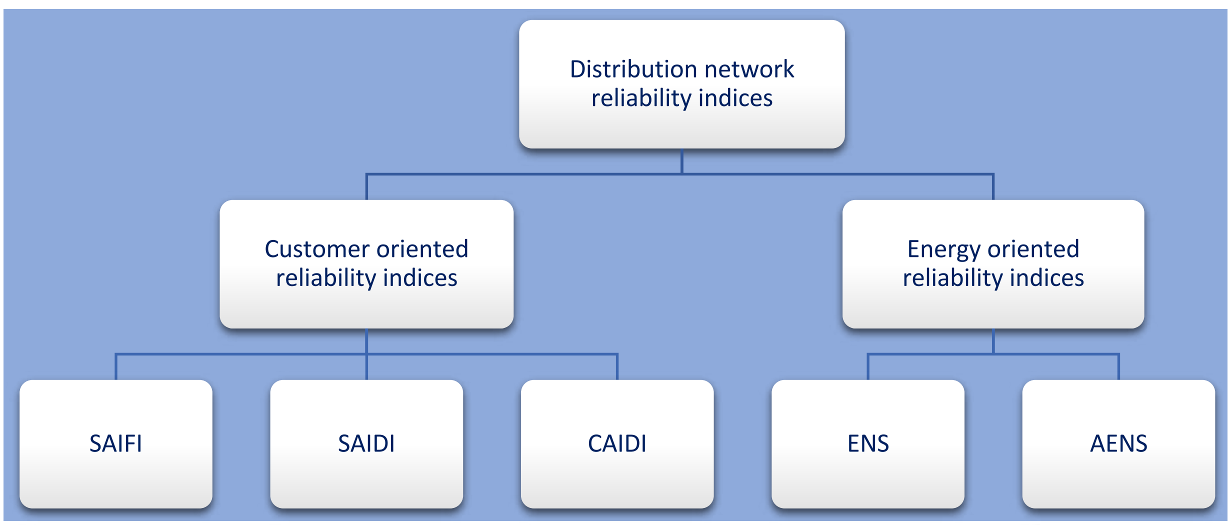


Figure 6.4: Classification of different reliability indices (Deb et al., 2018)

The typical causes of supply interruption are:

- Outages resulting in interruption
- Failure of distribution network equipment disrupting the operation of network
- Sudden increase in load leading to load shedding
- Scheduled maintenance
- Damage to infrastructure due to extreme weather

The details of the reliability indices have been highlighted below.

System Average Interruption Frequency Index (SAIFI) is the average number of interruptions a customer experiences within a certain period. It is determined using the formula given below.

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served}$$

Where λ_i is the failure rate and N_i is the number of customers for location i.

System Average Interruption Duration Index (SAIDI) is the average outage duration for each customer served and is determined using the formula given below.

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} = \frac{sum\ of\ all\ customer\ interruption\ durations}{total\ number\ of\ customers\ served}$$

Where, $U_i$is the annual outage duration of bus i.

Customer Average Interruption Duration Index (CAIDI) is the average outage duration that any single customer would experience and is expressed as shown below

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i} = \frac{sum\ of\ all\ customer\ interruption\ durations}{total\ number\ of\ customer\ interruption} = \frac{SAIDI}{SAIFI}$$

Energy Not Served (ENS) gives the total energy not supplied by the system and is expressed as

$$ENS = \sum L_i U_i$$

Where $L_i$is the load demand of bus i

Average Energy Not Served (AENS) is the average system load curtailment index and is given as shown below

$$AENS = \frac{\sum L_i U_i}{\sum N_i}$$

EV charging adds a significant amount of load to the system, due to which the failure rate, failure severity and the outage duration are increased from base case scenario without EV integration. This has contributed to the degradation of each of the five reliability indices, although the level of degradation is relative to the percentage of EV load in the system. However, it has been found that increase in number of fast chargers without necessary upgradation to the distribution network infrastructure severely deteriorates the reliability of the power supply.

Case Study

The impact of EV integration on reliability of power supply has been studied in the IEEE 33 bus system. (Deb et al., 2018)

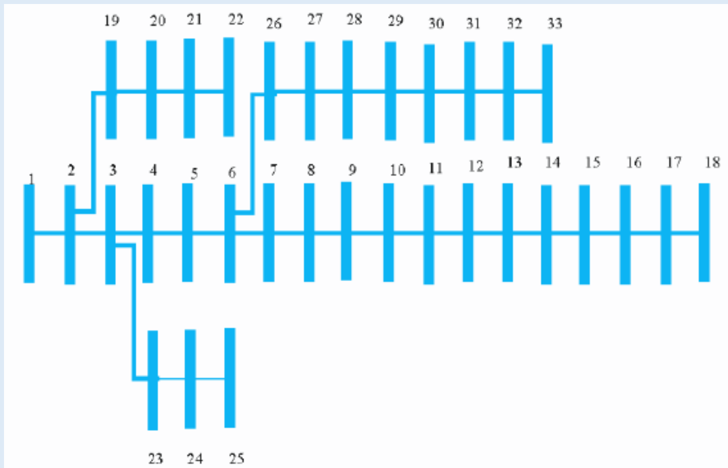


Figure 6.5: IEEE 33 bus test network

Considering each EV charger to consume 50kW of power, the scenarios chosen for study are listed in Table 6.1:

Table 6.1: Scenarios of the study

Case	Description	Increase in Load (kW)
Base case	No EV charging	-
2	Fast Charging station placed at bus 2	1500
3	Fast Charging station placed at bus 2	3000
4	Fast Charging station placed at bus 2	7500
5	Fast Charging station placed at bus 2 and 19	3000 (1500 each)
6	Fast Charging station placed at bus 14	1500
7	Fast Charging station placed at bus 14 and 15	3000 (1500 each)

To calculate the reliability, the parameters such as failure rate, unavailability and number of customers have been considered from (Bhadra & Chattopadhyay, 2015). Based on their analysis the reliability indices for the different scenarios are

Case	SAIFI (Interruptions/year)	SAIDI (h/year)	CAIDI (h/interruption)	AENS (kWh/year)
Base case	0.0982	0.5048	5.1385	1.9369
2	0.1195	0.6321	5.2915	10.2612

3	0.1407	0.7594	5.3984	33.27
4	0.2043	1.1413	5.5858	314.5049
5	0.1361	0.7155	5.2558	16.3547
6	0.1235	0.7568	6.1341	15.1578
7	0.1366	0.8448	6.1850	23.9717

Compared to base case, the reliability indices have worsened in all the simulated scenarios. The worst hit on reliability can be observed for case 4, when 7500 kW charging load was put on bus 2.

6.8 Impact of Harmonics on Transformer Life

Presence of harmonics increase the flow of eddy current, thus increasing the heat generations in the transformer. Harmonics also increases the skin effect due to which the current flow faces increased resistance. The extra heat generation significantly reduces the operating life of the insulation on the transformer. The estimation of transformer loss of life is based on the rate of deterioration of the insulating material (Atla et al., 2019).

The top oil temperature rise in a transformer is calculated using the formula given below.

$$\Delta\theta_{T0} = \theta_{T0-rated}\left(\frac{P_{LL}+P_{NL}}{P_{LLrated}+P_{NL}}\right)^{0.9}$$

where

$\theta_{T0-rated} = $ *top oil temperature rise over ambient under rated conditions*

$P_{LLrated} = $ *load losses under rated conditions*

$P_{NL} = $ *no load losses*

$P_{LL} = $ *load losses, increased to account for harmonic load currents*

The temperature rise of the winding over top oil is calculated as given below,

$$\phi_g = \phi_{gR}\left(\frac{P_{LL}}{P_{LLR}}\right)^{0.8}$$

where

$$\phi_{gR} = \text{Rated hot spot winding temperature rise over top oil}$$

The hot spot temperature is calculated using the formula given below.

$$\phi_H = \phi_A + \Delta\theta_{T0} + \phi_g$$

where

A is the ambient temperature

H is the hot spot temperature

The relative aging factor and real life of a transformer can be expressed as shown below

$$F_e = \exp\left(\frac{15000}{383} - \frac{15000}{\phi_H + 273}\right)$$

Where F_e is the relative aging factor

$$Life(pu) = 9.8 \times 10^{-18} e^{\left(\frac{15000}{\phi_H + 273}\right)}$$

Estimated life = Life(pu) x Normal insulation life

Using the above methodology for a transformer with the specifications as given in Table 6.2 and harmonic spectrum as given in Table 6.3, the calculated transformer life has been given in Table 6.4. As seen, with high Current Total Demand Distortion (ITDD) content, the transformer life is significantly reduced.

Table 6.2: Input data for transformer

	DESCRIPTION	VALUE
1	Transformer Rating (kVA)	200
2	Temperature base for losses (^{0}C)	75
3	No load losses (W)	500
4	Winding losses (W)	1963
5	Winding eddy current losses (W)	177
6	Other stray losses (W)	294
7	Top oil rise over ambient (Rated) (^{0}C)	65
8	Hot spot temperature rise over top oil (rated) (^{0}C)	10
9	Normal insulation life (yrs.)	20.55

Table 6.3: Harmonic Spectrum (Atla et al., 2019)

CASE	%ITDD	HARMONIC SPECTRUM (HARMONIC ORDER)								
		1	5	7	11	13	17	19	23	25
CASE 1	22	1	0.1760	0.1100	0.0447	0.0264	0.0118	0.0106	0.0087	0.0086
CASE 2	15	1	0.0938	0.0963	0.0632	0.0304	0.0102	0.0037	0.0043	0.0092
CASE 3	10.8	1	0.0577	0.0718	0.0463	0.0286	0.0092	0.0055	0.0068	0.0030
CASE 4	7.5	1	0.0567	0.0457	0.0136	0.0108	0.0046	0.0037	0.0027	0.0023
CASE 5	8	1	0.0494	0.0507	0.0333	0.0160	0.0053	0.0019	0.0022	0.0049

Table 6.4: reduced transformer life due to current harmonics

CASE	%ITDD	AVAILABLE TRANSFORMER LIFE (YRS.)
CASE 1	22	6.3
CASE 2	15	9.2
CASE 3	10.8	14.5
CASE 4	7.5	19.6
CASE 5	8	17.4

Case Study: Impact of EV charging on an ideal distribution feeder

The following case study have been carried out to determine the impact of EV charging on an ideal distribution feeder. As shown in Figure 6.6, the distribution feeder has a voltage level of 0.4 kV and is connected to the external grid through a 0.2 MVA 10/0.4 kV transformer. There are 27 different residences along the feeder with each residence having an EV. The active and reactive power drawn by the connected loads of the feeder have been given in Figure 6.7. All the EVs are considered to be Nissan Leaf with a battery of 24 kWh. The residential charging option have been assumed to be a three phase 11 kW AC charger.

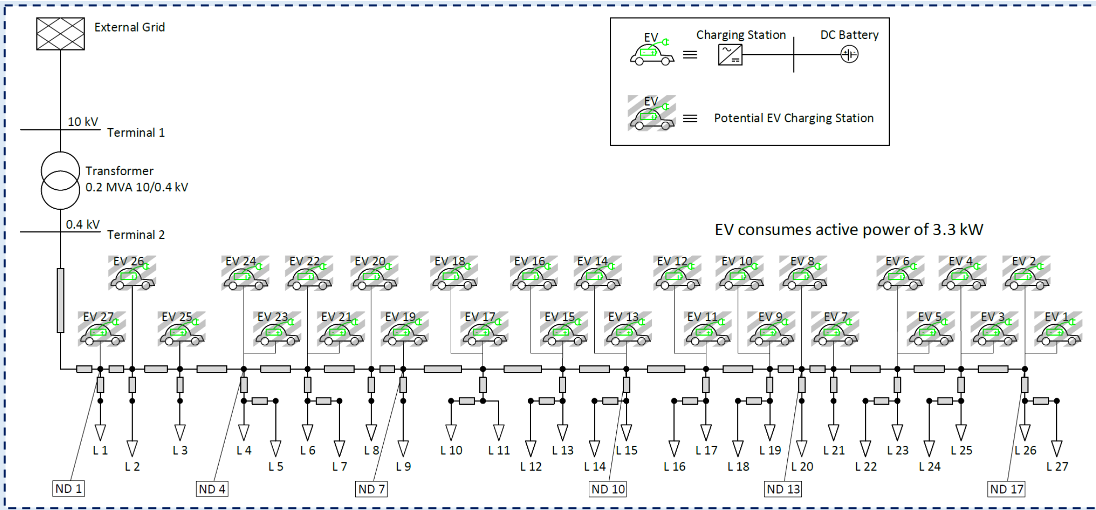


Figure 6.6: Distribution feeder

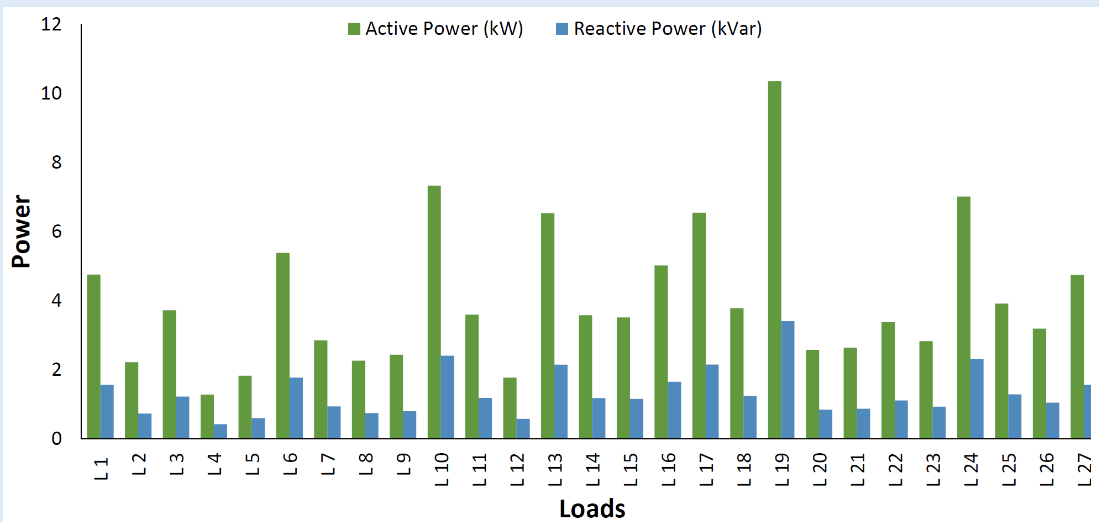


Figure 6.7: Static loads in the feeder

Using the above-mentioned assumptions, the impact on the feeder voltage, hosting capacity and power losses have been analysed under different EV charging load levels.

To monitor the impact of EV penetration on the distribution feeder, the feeder voltage has been measured at different nodes along the length of the feeder. The location of these nodes has been shown in Figure 6.6. Figure 6.8, shows the variation of voltages at the different nodes of the feeder when the number of EVs charging simultaneously have been increased from 0 to 27. When no EVs were charging the voltage at the start of the feeder (ND_001) had the highest voltage level at around 1.008 pu and the voltage at the rear end of the feeder (ND_017) had the lowest voltage level at 0.98 pu. The voltage along the entire feeder length went further down as the number of EVs charging simultaneously was increased, with a higher drop in voltage seen for ND_017 then for ND_001.

Next, the impact of voltage at ND_017 is monitored, for two different EV connection orders under different penetration levels. In the first case, the EVs are connected from the rear end of the feeder, i.e., the first EV is connected to the final node in the feeder, the 2nd EV is connected to the penultimate node and so on and the final EV is connected to the starting node of the feeder. In the second case, the EVs are connected from the start of the feeder, i.e., the first EV is connected to ND_001, the 2nd EV is connected to ND_002 and so on until the final EV is connected to the final node. For both the cases the voltage at ND_017 is monitored to check if there is any difference on feeder voltage if the order of EV loading is altered.

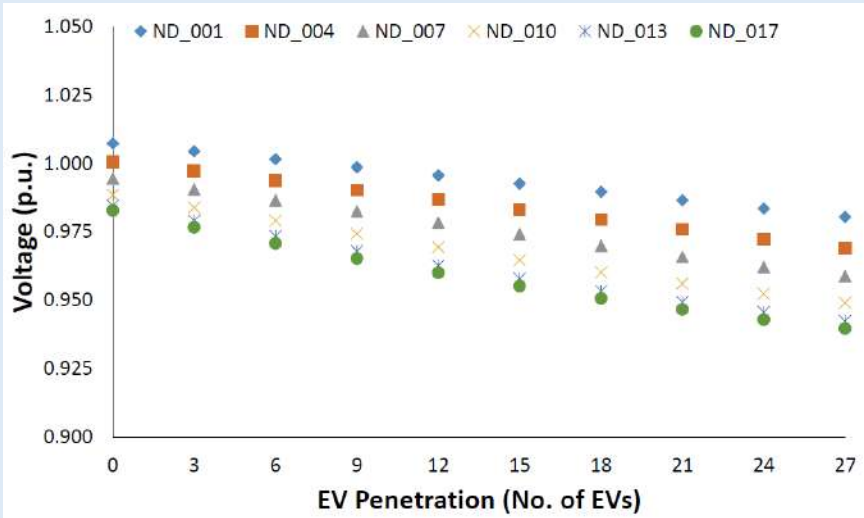


Figure 6.8: Feeder voltage at different nodes under different EV penetration levels

As seen in Figure 6.6.9, if no EV is connected then the voltage at ND_017 is same for both the cases. But as the number of EVs increases, the voltage is worse for Case 1, where the EVs are connected from the end of the feeder then for Case 2. This is because, when the EVs are connected from the rear end of the feeder, the current drawn flows through the entire length of the feeder, which increases the voltage drop across the feeder. If the EV is connected to the start of the feeder, then no excess current flows through the feeder, due to which the voltage drop is reduced.

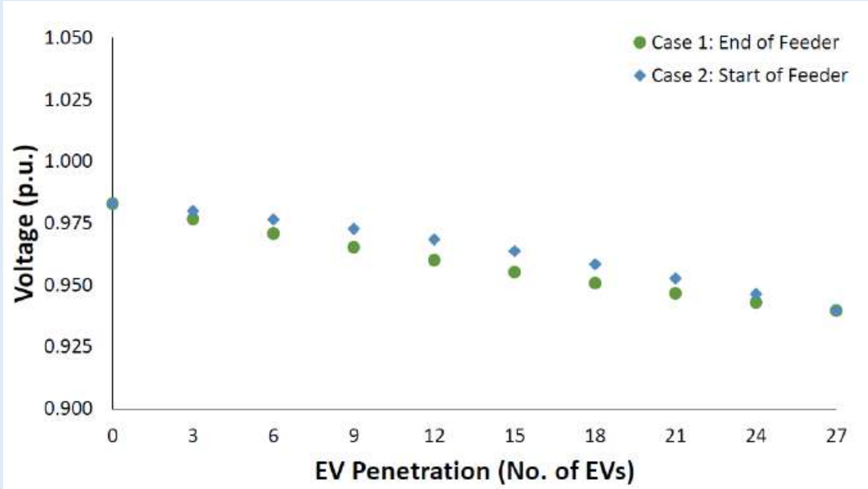


Figure 6.9: Voltages at ND_017 for different levels of EV penetration

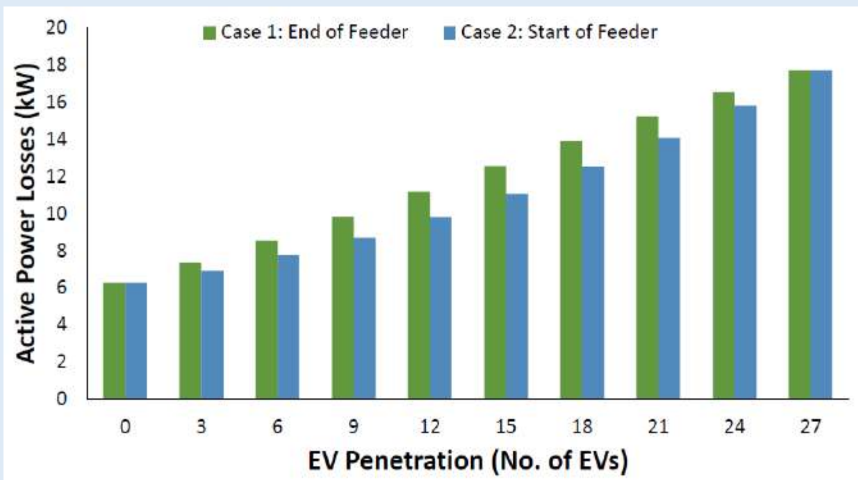


Figure 6.10: Total active power losses for different penetration levels of EVs

The active power losses due to increasing EV penetration in the feeder has been shown in Figure 6.10. Here, the active power loss is more for cases where the EV loading is done for the tail end of the feeder which can be attributed to the increase in the length of line i.e., higher resistance, that the current has to flow through, which increases the I^2R losses.

Chapter 7: Grid Support from EVs

Although the primary application of an EV charger is to charge up the EV to satisfy the EV user's transportation needs, EVs can potentially perform a range of grid support services by controlling the charging of EV or by allowing bidirectional flow of power. From the perspectives of transmission system operators and the distribution operators, EVs can be utilized as a mobile storage unit to benefit the different grid operators. The controllable nature of EV charging makes them ideal for providing ancillary services. Different strategies can be utilized for these ancillary services provisions. Ancillary service markets generally have a minimum bid volume, so an EV as a single entity cannot participate in these markets. An aggregator must group a fleet of EVs for participation in ancillary service markets to maintain the minimum bid volume. The different applications of an EV charger have been categorized in Figure 7.1.

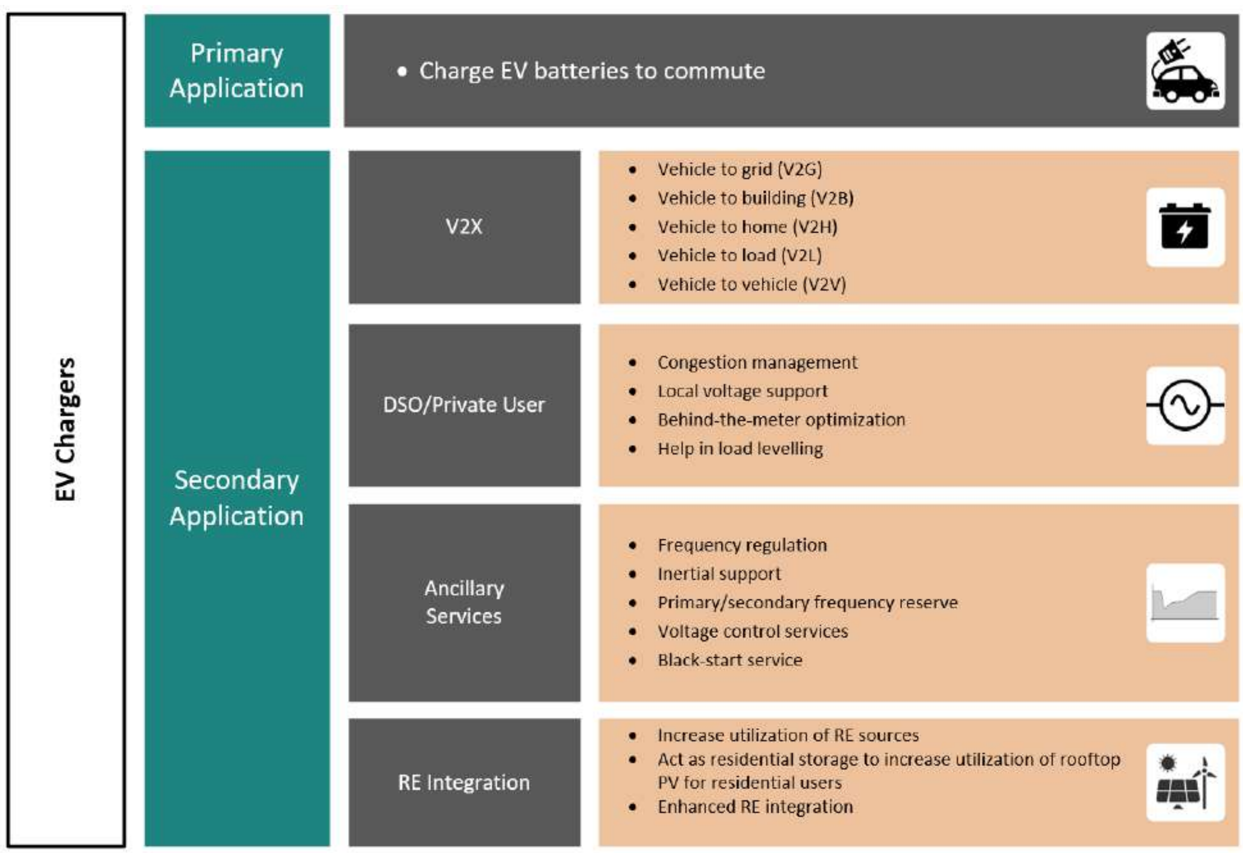


Figure 7.1: Applications of EV charger

7.1 Voltage Control

The higher power demand of EV charging, deteriorates the voltage profile in distribution networks. There two ways in which this voltage drop may be mitigated are,

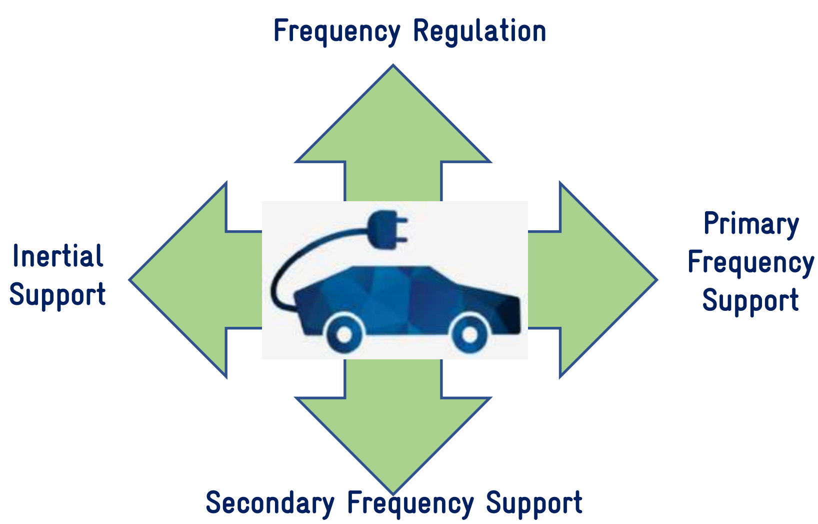
Local Voltage Control	Coordinated voltage control

Local voltage control is one of the more straightforward methods of achieving voltage control, which is implemented based on droop control. This is achieved by adjusting the active power set points of the chargers based on the terminal voltage deviation. However, with just local control, the optimal solution may not be achieved, and each EV may operate at below their optimal levels. So, local voltage control is generally complemented by a coordinated control. A central controller controls each EV, and the central controller optimally sets the operating setpoints.

Again, depending on the type of grid, different settings maybe defined for voltage control. In LV distribution networks where R/X ratio is high, reactive power control may not be as efficient as active power control in maintaining the voltage level within the stable operation limits. So in these networks, the EVs are generally configured to reduce their active power to improve the terminal voltages, rather than providing reactive support (CIGRE, 2015).

7.2 Frequency Control

The EVs may participate in a variety of frequency support services as shown below.



7.2.1 Frequency Regulation

The transmission system operator generally provides regulation signals as responses to the frequency deviations within the stable operational limits. These regulation signals are introduced to equate the finer differences between the actual generation and load in real-time. A fleet of EVs can participate in frequency regulation by controlling the active power set points based on the regulating signals. However, it needs to be kept in mind that as the primary objective of an EV is to fulfil the customer's travel needs, so there needs to be sufficient amount of charge remaining in the EV battery when the EV is plugged out from the network. The EV charging set point P_{EV} is given by

$$P_{EV} = P_{charge} + P_{reg}, such\ that\ |P_{EV}| < P_{rated}$$

where, P_{charge} is the initial charging power and P_{reg} is the regulating power.

7.2.2 Inertial Support and Primary Frequency Support

In the event of a sudden failure of a generator or a transmission line, or the sudden increase of a large amount of load, there is a sharp drop or rise of frequency depending on whether there is an active power deficiency or surplus in the grid. The rate of change of frequency (RoCoF) is arrested by the inertia of the system. The system inertia is the kinetic energy stored in the system due to the rotating masses of the synchronously connected conventional generating units. With the increasing replacement of the conventional generating units by renewable sources, the inertia in the system has seen a steady decline over the year, as the renewables sources do not generally provide inertial support, which has forced the system operators to look for other sources of inertia. Here, it needs to be mentioned that the effect of system inertia is more pronounced in the initial seconds post a contingency event. After a brief period of fewer than 10 seconds when the frequency deviation exceeds a predetermined setpoint, the governor operation of the conventional generator kicks in, the generator starts providing primary frequency support.

EVs charging may be exploited in this regard, to provide inertial and primary frequency support using the control structure as shown in Figure 7.2. Here two loops are utilized, one for provision of emulated inertia and the other for provision of primary frequency reserve. The derivate gain is a measure of the controller's sensitivity to the rate of change of frequency. This behaves as emulated inertia and can be written as shown below,

$$\Delta P_{inertia} = k_{in} \frac{d}{dt}(\Delta f)$$

where, k_{in} is the emulated inertia gain/sensitivity. The other control that is based just on the frequency deviation is termed as primary frequency control and can be written as

$$\Delta P_{PFC} = k_p \Delta f$$

where, k_p is the droop coefficient.

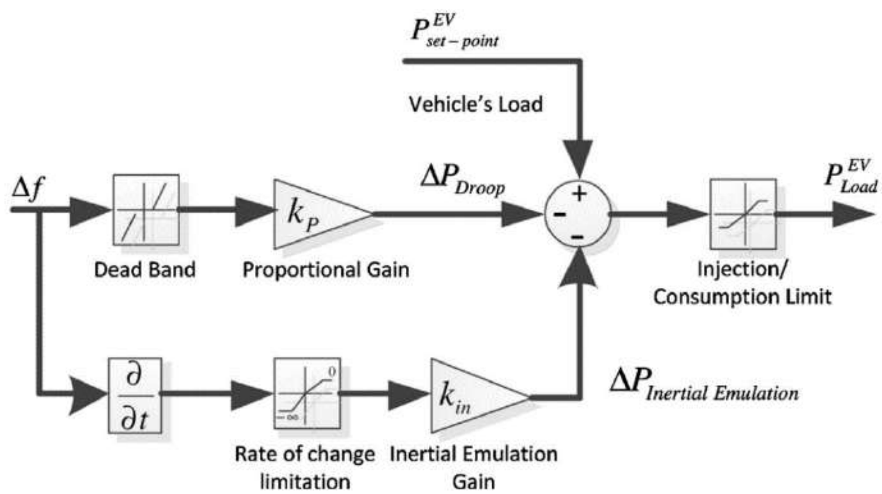


Figure 7.2: Control structure of EV providing emulated inertia and primary frequency reserve (Almeida et al., 2015)

7.2.3 Secondary Control

In secondary frequency control, the Automatic Generation Control (AGC) operation is the centrepiece in the control hierarchy. With large-scale EV deployments, the TSO who is responsible for the AGC, will acquire the secondary reserve from the generation companies (GENCO) and from the EV aggregators. If there is a contingency in the system, following the inertia operation and the primary frequency reserve, the AGC, utilizes the secondary reserve to bring the frequency back to its nominal value, by sending active power set-points to all the participants of the secondary reserve. If the EV aggregators are participating in the provision of secondary reserve, then the AGC signal will send setpoints to adjust the aggregate load from the EV fleet. The EV aggregator will then decompose the AGC signal to individual set points for each of the EVs willing to participate in this service.

The Area Control Error (ACE) signal is generated using the deviation of the system frequency f_i from the system nominal frequency f_{REF} corrected using the frequency bias factor B, and the tie-line active power flows Pif_i, in relation to the scheduled interchange flows Pif_{REF}. The ACE signal is the fed through an integral controller with gain K_i, $Pe^{ini}{}_m$ is the current dispatch of machine m, fp_m is the participating factor and $Pref_m$ is the new active power set point value. Pa_i^{ini} is the initial load of the EV aggregator and fp_{Ak} and $Pref_{a1}$ are the EV aggregator participation factor and the new active power set-point.

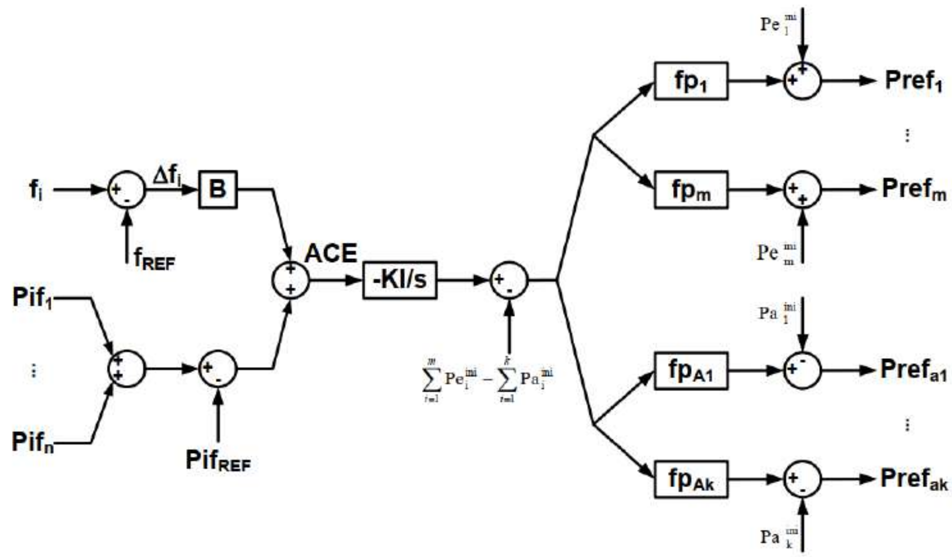
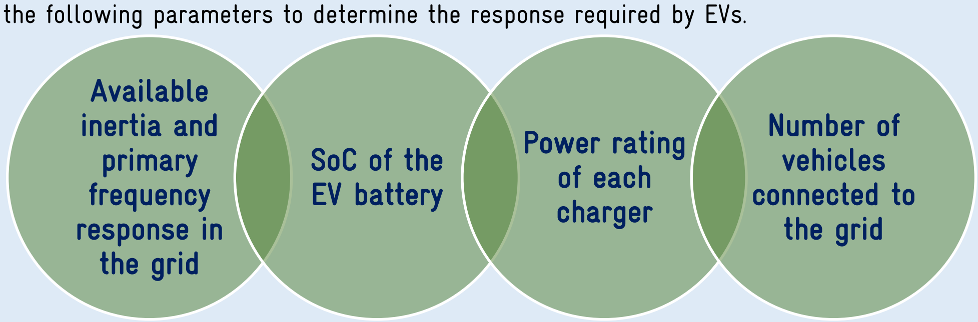


Figure 7.3: AGC operation including EV aggregator **(CIGRE, 2015)**

Case Study: Inertial and primary frequency support from EVs.

In this case study conducted at IIT Bombay, a fleet of EVs have been utilized to provide synthetic inertia to the grid during periods of low inertia as well as provide primary frequency response to keep the system performance within satisfactory conditions during active power mismatch events. The proposed methodology considers the following parameters to determine the response required by EVs.



The proposed model has been studied in a modified IEEE 39 Bus Test System shown in Figure 7.4. A transportation model was also developed to simulate the stochasticity of the number of cars connected to the grid at any point in time. To have a reduced grid inertia, 7 wind power plants with Type 4 wind turbines (WT) without inertial support have been added to the system. The generation from the wind plants was given a must run status. So based on the RE generation and the system load, the number of synchronous generators connected to the grid was varied, which eventually led to variation in grid inertia. To make up for the lost inertia the EVs were provided with a synthetic inertial controller that responded to the change in the grid frequency.

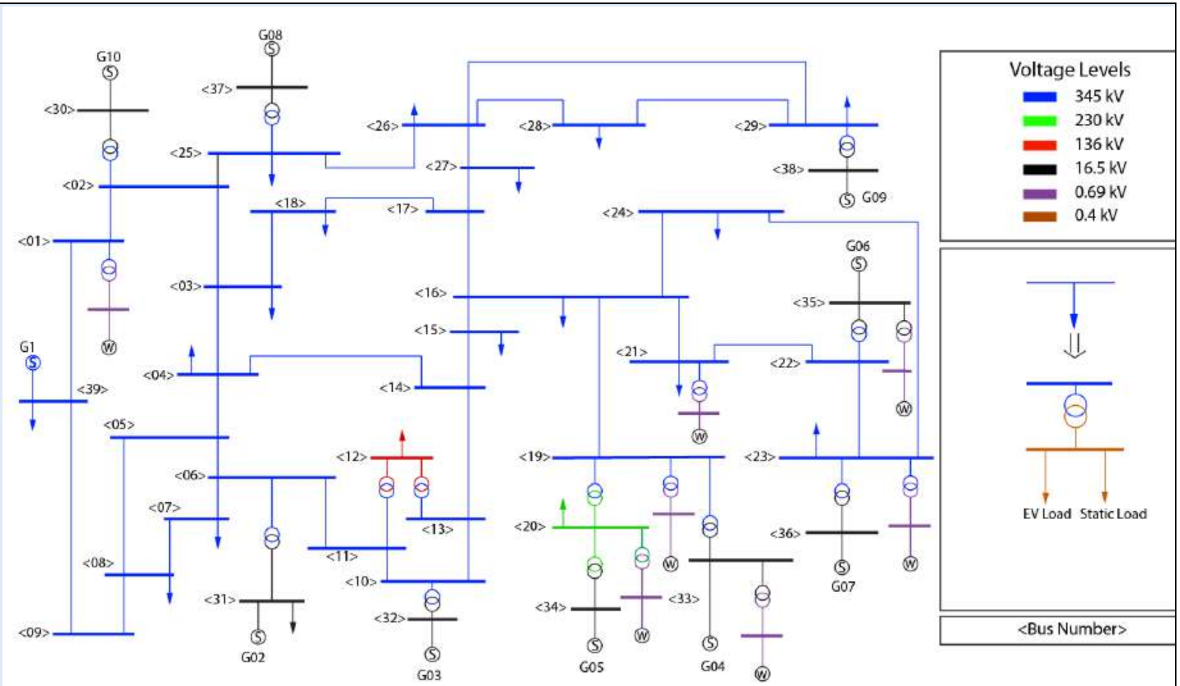


Figure 7.4: Modified IEEE 39 Bus Test System

To determine the impact of inertial support from EV, the system performance was studied for a fixed step increase in load. This increase in load event was given to each hour, so that different scenarios are created with different grid inertia values. As seen in Figure 7.5, without support from EV, the frequency nadir was much worse, but with support from EV, the frequency nadir remained at a constant value of around 49.4 Hz. Similarly, from Figure 7.6, the RoCoF performance can also be seen to much improved with the added inertial support from EV. The EVs were also modelled to provide primary frequency response. Figure 7.7 shows the quasi-steady state frequency after the primary frequency response has been provided and before the secondary response kicks in. The quasi-steady frequency also shows the improved grid performance with the added support from EV.

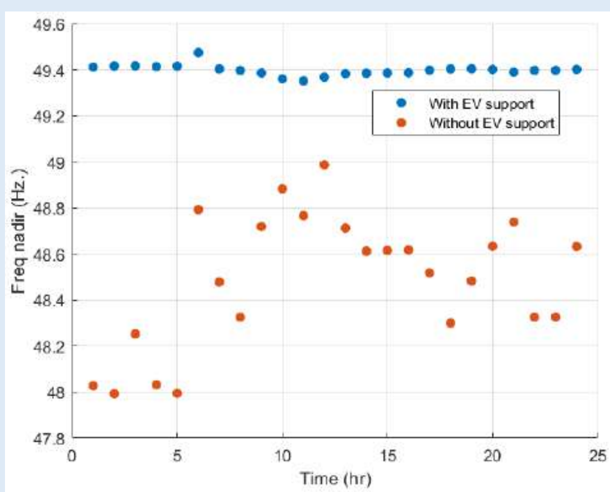


Figure 7.5: Frequency nadir with and without EV support

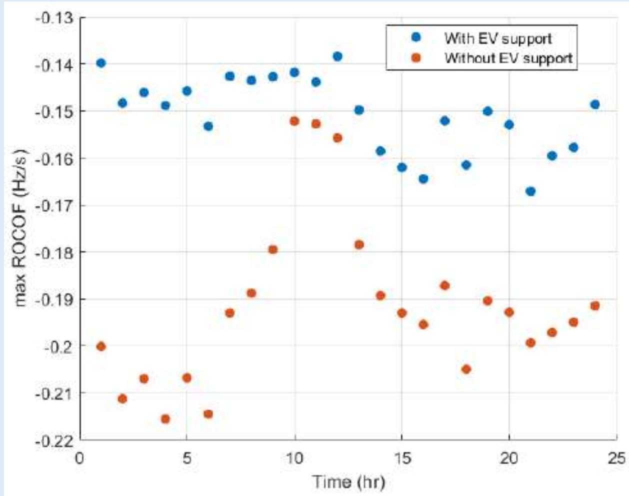


Figure 7.6: Max RoCoF with and without EV support

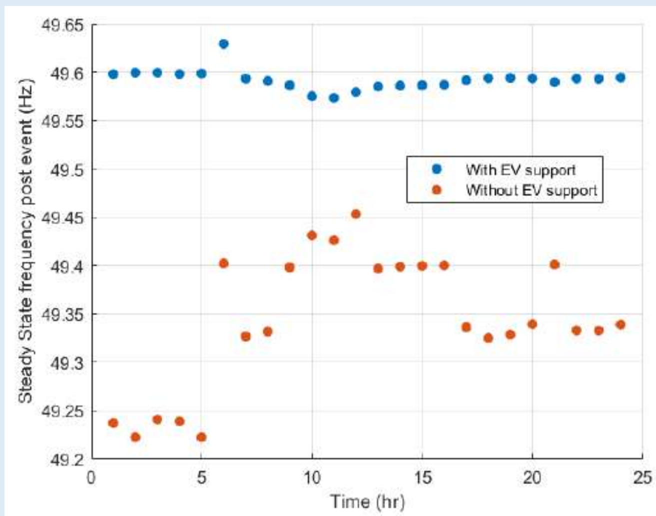


Figure 7.7: Quasi steady-state frequency with and without EV support

7.3 Vehicle2X System

V2X is the concept of discharging the EV battery in order to serve secondary purposes. It can be used to manage charging to provide grid support services (V2G), manage energy within a home (V2H), a building or microgrid (V2B) or other purposes such as emergency power for off-grid situations like campsites as shown in Figure 7.8.

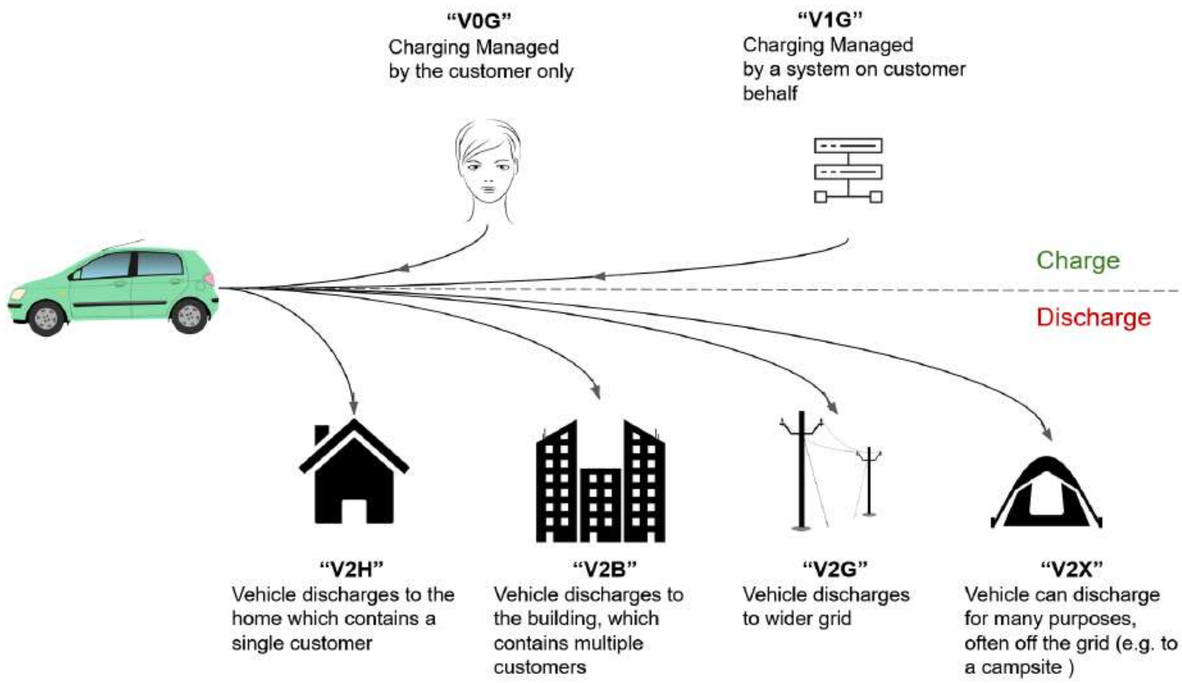


Figure 7.8: Different domains of charging/discharging (Jones et al., 2021)

V2X technology needs added electrical infrastructure compared to standard charging or even smart charging. It needs a bidirectional inverter to convert the DC power from the batteries to AC power synchronized to the grid. This conversion equipment is generally housed in the EVSE as seen in Figure 7.9. A robust communication infrastructure is also needed to relay information back and forth between the EV and grid (in case of V2G) or any other energy management software. Further, additional technical requirements must be met in case of V2X applications such as appropriate Loss of Mains (LOM) protection to ensure that the EV does not feed power to the grid during a fault or when maintenance may be underway in the network. Also, two metering would be necessary to measure electricity exchanges with the grid for settlement purposes.

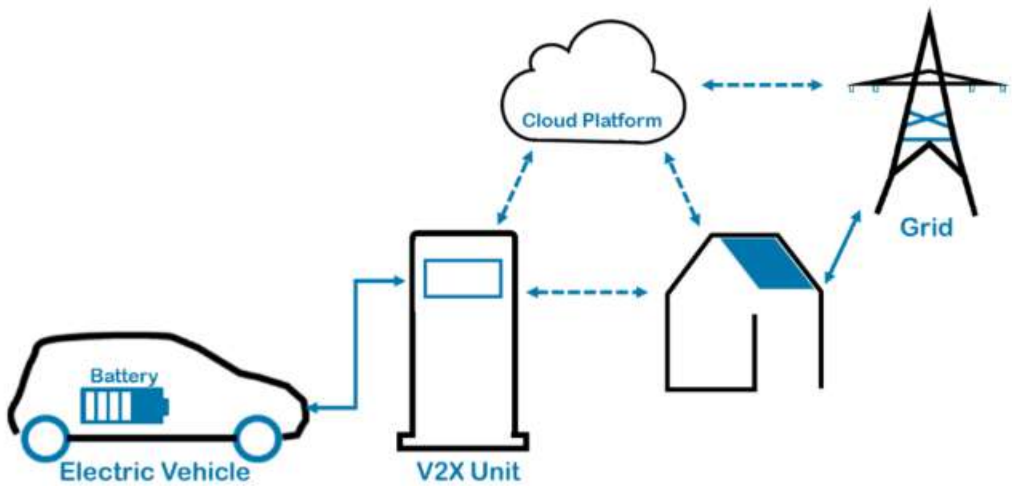


Figure 7.9: V2G schematic **(Corchero et al., 2019)**

The potential application of V2X technologies is given below,

7.3.1 System Services to the TSO (V2G)

These services include frequency regulation, participation in reserve markets for system stability etc. The services that are best suited for V2G are those characterized by fast response times, minimal energy throughput, short durations, and fewer activations. Another important aspect is that since the TSO generally puts a limit on the minimum allowable capacity for participating in these markets, an individual EV cannot generally participate in these markets. An aggregator is required to coordinate the response from a fleet of EVs in order to meet these requirements.

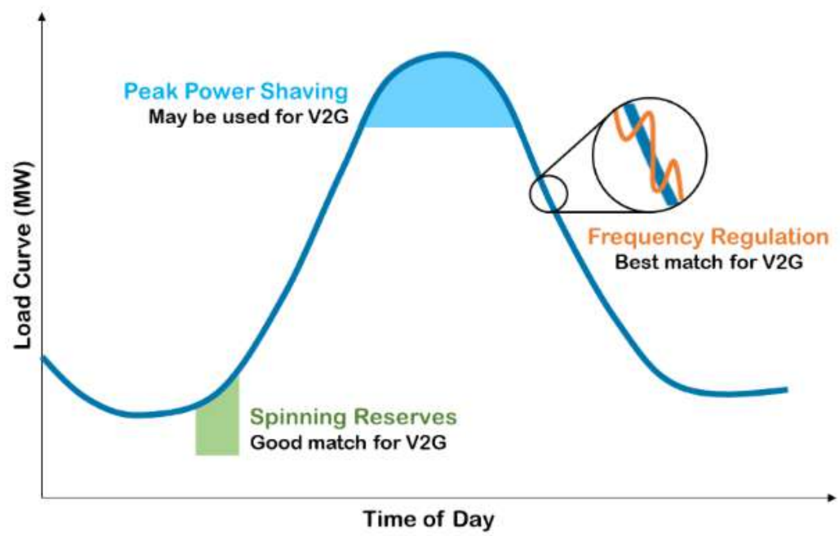


Figure 7.10: Participation of V2G in providing different services to TSO **(Corchero et al., 2019)**

7.3.2 System Services to the DSO (V2G)

V2G can also provide services to the DSO, such as congestion management and voltage support services. But similar to TSO system services, an aggregator is required to coordinate a fleet of EVs' behaviour to meet the minimum capacity requirement. The value of these services will be highly correlated to the location of the aggregator and the service requirement zone.

7.3.3 Behind-the-Meter Optimization (V2B)

Behind the meter optimization is mainly utilized by private residences, where an EV user can optimally schedule the EV charging/discharging in response to the dynamic electricity prices. Unlike services to TSO or DSO, control of behind the meter V2B is not generally controlled by a central energy management system of a fleet aggregator. Each user schedules their own charging/discharging based on the electricity prices. Three types of charging methods are utilized here,

- **Time of Use (ToU) tariffs:** Here, the electricity price is a function of time, and the consumers schedule their EV charging as a response to this variable price. The consumer creates value by charging the EV at low off-peak periods when the electricity price is low and discharging the EV during peak periods when the price is high.
- **Capacity Charges:** A residence is generally subjected to maximum capacity limits, surpassing which leads to penalization of the customer. V2B maybe used in this regard to reduce the capacity requirements during residential peak load periods.

- **Self-consumption:** This is used for integration of on-site generation such as rooftop solar PV. If a building has asymmetric import and export prices, the V2B can help add value by maximizing self-consumption thus reducing usage of higher priced grid electricity.

7.3.4 Back-up Power Supply (V2H)

In locations which are prone to system outages, V2H can bring great value in providing emergency power. However, the value of this service is also dependent on the building type and user requirements. For example, in UK Value of Lost Load (VoLL) varies between INR 7,17,766 /MWh (EUR 8,150 /MWh[1]) and INR 45,54,684/MWh (EUR 51,712 /MWh) depending on the time of day, season and user type.

7.4 Battery degradation

The battery life is characterized by

- Calendar aging
- Cycle aging

Calendar aging is the natural loss of life of the battery, and cycle aging is the loss of battery health due to charging and discharging of batteries. The degradation of battery health is accelerated by the following factors.

- High temperature
- High SoC
- High cycle count
- High cycle current
- Large Depth of Discharge (DoD)

7.4.1 Calendar Aging

Battery temperature and SoC are the two primary factors influencing calendar aging of battery. Temperature has a significant effect on the performance, safety and cycle lifetime of a battery. Batteries function best at room temperatures, and the battery health deteriorates, when the ambient temperature deviates further from room temperature. Th effect of temperature on the cycle aging of battery has been shown in Figure 7.11. With increase in deviation of ambient temperature from the room temperature a greater loss in capacity is

[1] The currency conversion rate is, EUR 1 = INR 88.08, as of July 19, 2021.

seen due to calendar aging. Similarly, for SoC values it can be seen in Figure 7.12 at an unused battery at higher SoC leads to more calendar aging.

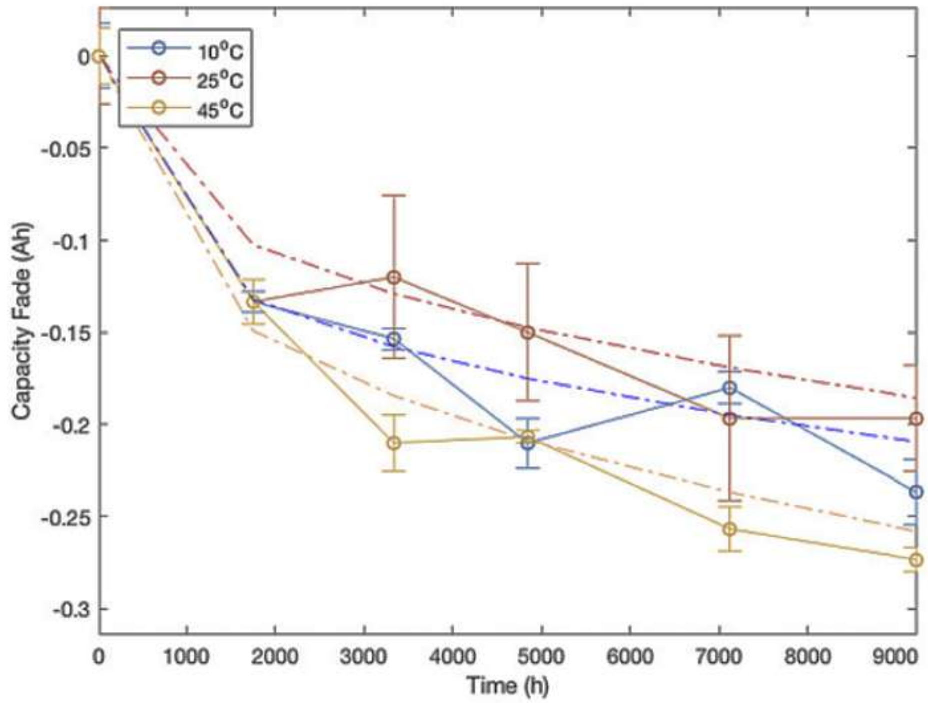


Figure 7.11: Li-ion battery degradation during storage as a function of temperature(Battery capacity is 3 Ah) (Uddin et al., 2017)

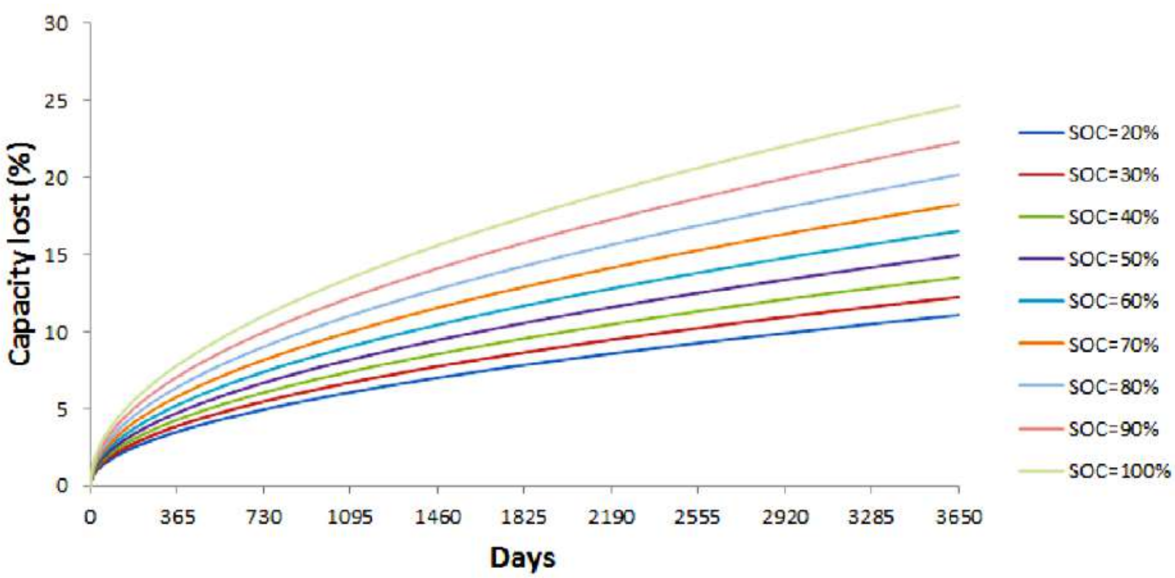


Figure 7.12: Capacity lost for different SoC storage values at 25^0 C **(Pelletier et al., 2017)**

7.4.2 Cycle Aging

Cycle aging is influenced by the C-rate, the depth of discharge of each charge cycle, the number of charge discharge cycles and the energy throughput. With increase in C-rate the cycle life of the battery decreases i.e. the number of cycles that the battery can go through before losing 20% of its energy capacity decreases as shown in Figure 7.13. It is generally seen that after 4000 cycles capacity degradation is 15% at 1C and 17% at 4C charging (Bhagavathy et al., 2021). A similar trend is also seen for DoD for each cycle, where the cycle life decreases for increase in DoD.

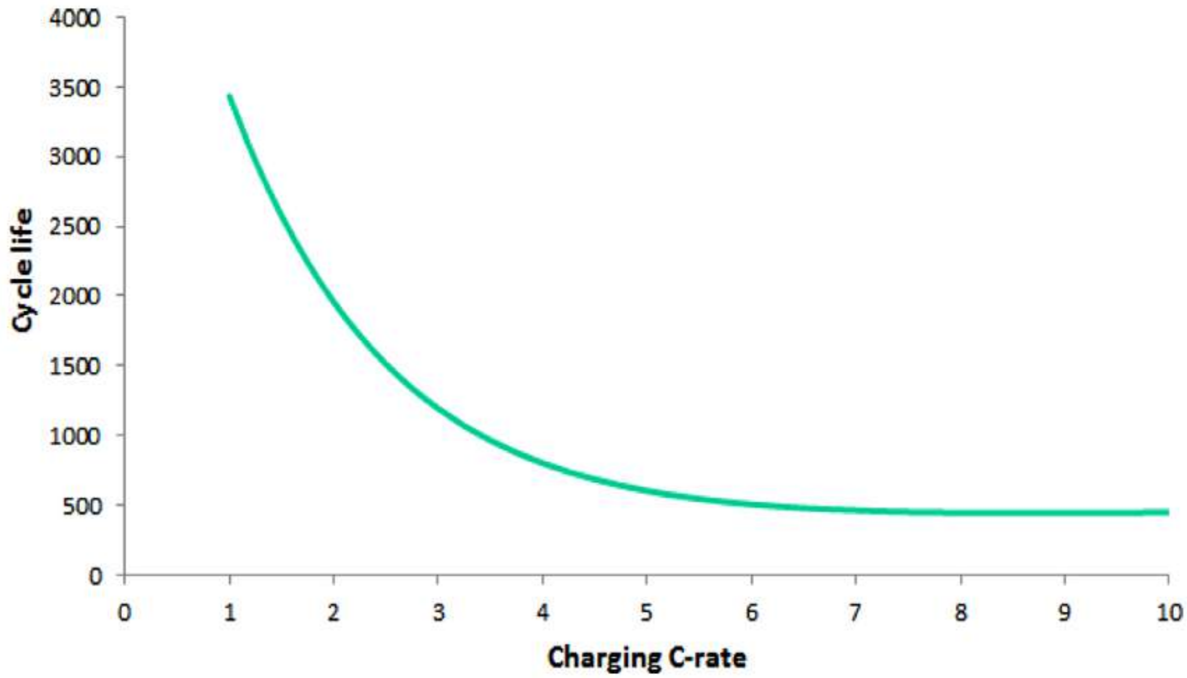


Figure 7.13: Cycle life of battery vs Charging C-rate **(Pelletier et al., 2017)**

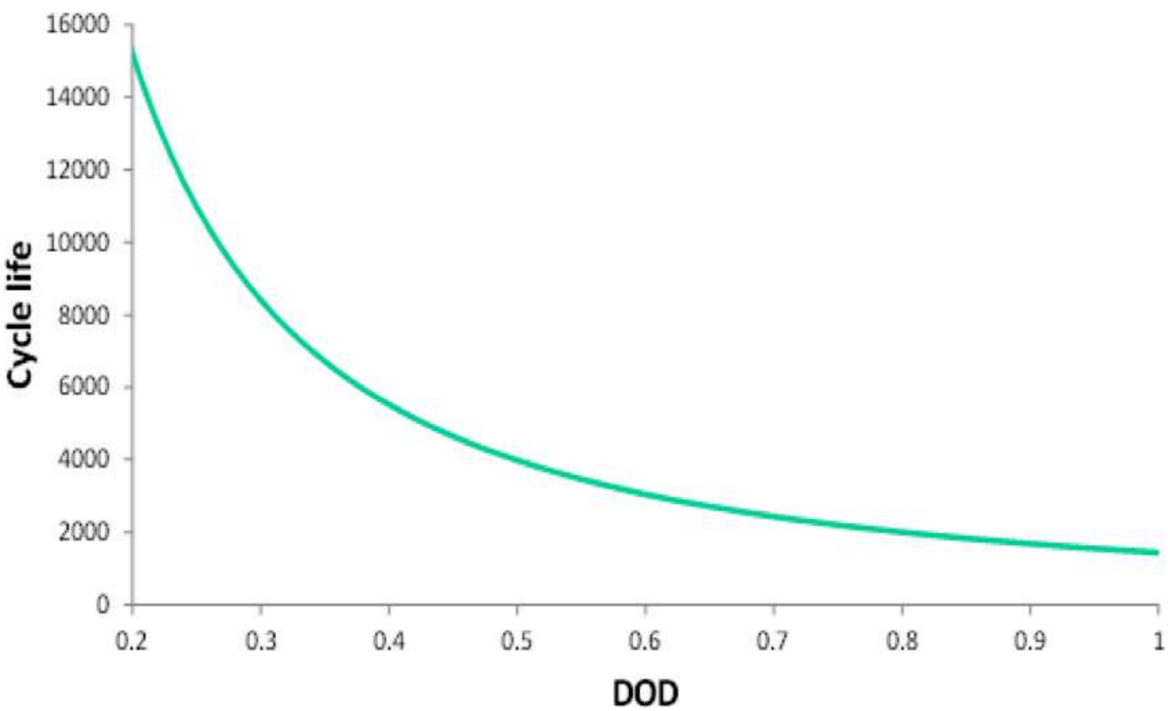


Figure 7.14: Cycle life of battery vs DoD (Pelletier et al., 2017)

7.4.3 Impact of charging on battery health

Table 7.1 shows the charging details for a few of the popular EVs in the global market. It can be seen that utilizing AC charging the average C-rate remains much below 1C, even for 50 kW DC charging the C-rate remains around 1C. As we have discussed early, with C-rate below 1C the battery health is not affected significantly. Only when the battery is charged at more than 1C, a noticeable impact is seen on the battery lifetime.

Figure 7.15, shows the remaining battery capacity with the distance accumulated by the EV, where each dot is an individual EV. It can be seen that even after accumulating 250,000 km, the battery has degraded by less than 10%.

Table 7.1: Charging details of a few of the popular EVs (Bhagavathy et al., 2021)

EV Model	Battery Capacity (kWh)	Charging power limit		C-rate in per hour by charger type			
		AC (kW)	DC (kW)	AC 7 kW charging	AC 22 kW charging	DC 50 kW charging	DC 150 kW charging
Tesla Model 3	55	11	170	0.13C	0.20C	0.91C	2.7C
Tesla Model S	100	16.5	250	0.07C	0.17C	0.5C	1.5C
BMW i3	42	11	49	0.17C	0.26C	1.17C	NA
Nissan Leaf	40 or 62	6.6	49	0.11C	0.11C	0.79C	NA
Renault ZOE	55	22	46	0.19C	0.40C	0.84C	NA
Hyundai IONIQ	40	7.2	44	0.18C	0.18C	1.10C	NA

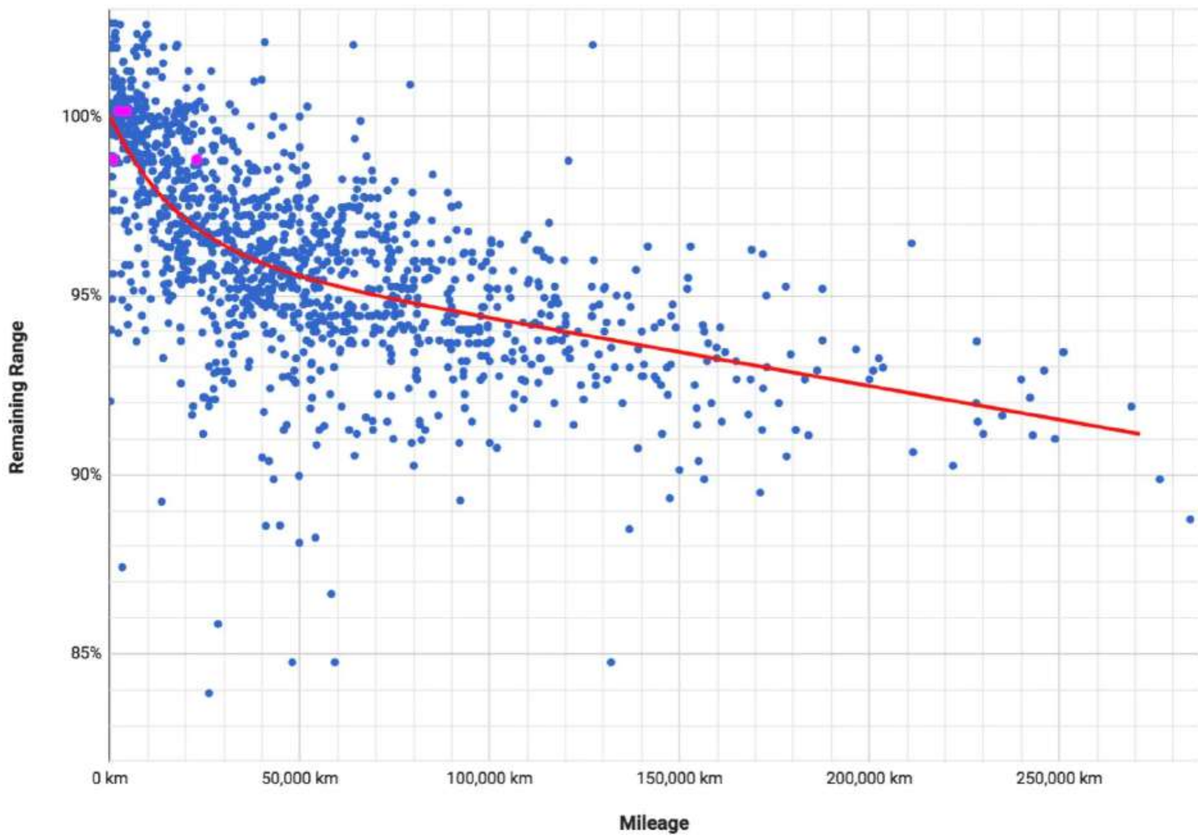


Figure 7.15: Tesla Model S/X mileage vs remaining battery capacity (Lambert, 2018)

7.4.4 Impact of V2G on battery

The impact of bidirectional charging on the health of the battery is dependent on the charging regime followed by the battery. In a study (Dubarry et al., 2017) the impact on commercial Li-ion cells was observed, if the charging regime is optimized to maximize the EV owners profit i.e. selling as much energy as possible to the grid. Its results showed that due to the increase in the cycle count as well as the increase in DoD of each cycle, the deterioration in battery health is more severe than without using V2G. As per their analysis, after 5 years with two V2G cycles per day the capacity of the battery faded by close to 20%, while without V2G, the capacity faded by only around 10%. However, in this scenario the battery control have been designed to maximize the usage of the battery in order for the EV user to earn maximum revenue.

As we have earlier discussed that, the health of a battery also depends on the storage SoC and also on the DoD of each cycle. So, another study tried the possibility of extending the life of battery by optimizing the V2G regime (Uddin et al., 2017). The discharging algorithm used by them calculated the expected degradation of battery when it is stored at its current SoC to the degradation of the battery due to the expected cycle. The battery was allowed to be discharged, only if the degradation due to discharging was more than the degradation due to storage. By optimizing the charge discharge cycle based on the impact on battery degradation the authors were able to reduce capacity by 9.1% over the course of a year compared to EVs without V2G.

Regarding V2G, it can be optimized to reduce battery degradation compared to uncontrolled charging. Fast battery degradation occurs at charging during high or low SoC. By maintaining the SoC of the battery between 30%-50% SoC, the health of the battery significantly improves (Hoke et al., 2013; Tan & Zhang, 2017). Optimized use of V2G services can help maintain the SoC of the battery within the optimal range. The authors implemented a V2G algorithm which improved the SoH of the battery between 6% and 3% over three months by keeping the SoC between 38% and 21% and using the 40% and 8% range for V2G services.

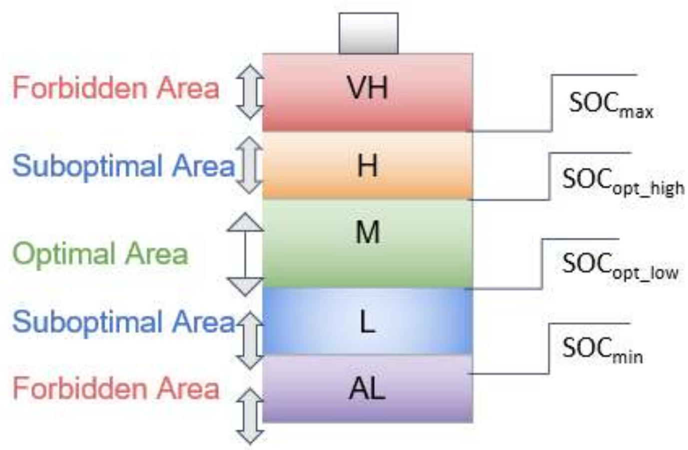


Figure 7.16: Battery maintaining SoC for optimal battery health (Tan & Zhang, 2017)

So, in essence although V2G would increase the cycle count, but the impact on the battery health is more complicated. The impact on battery health can be minimized and even reversed by optimizing the charge discharge cycle based on the battery health.

7.4.5 Impact on battery health based on grid support service

Different grid support service has a different impact on battery health based on the power and energy required by the service. In one study(Dai Wang et al., 2016), the authors compared three different grid support services and how they affect the battery health, which includes:

- Peak load shaving, where the EV charging is curtailed during the peak periods, or the EVs are also allowed to supply power to the grid during these peak periods.

- Frequency regulation, where the EVs help in correcting for short-term mismatch in generation and demand, by controlling their charging power of feeding back energy to the grid.
- Net load shaping, in which the EVs act as resources to facilitate high penetration of renewables, by balancing loads with intermittent generation.

The battery capacity loss for different grid support services is given in Figure 7.17. For extreme scenarios, the EVs provide grid support services daily for 10 years, and for more milder scenarios the EVs provide grid support services for 20 times a year. As can be seen, using EVs for net load shaping daily for 10 years has a significant impact on the battery health due to high DoD for each cycle and the increased number of cycles. In fact, for all the extreme cases, where grid services were provided daily, the increase in the number of cycles has increased the average capacity loss. For the milder cases too, the worst performance is seen for net load shaping support followed by peak load shaving and frequency regulation having the least impact on the battery health. However, it is also worth noting, that compared to the baseline scenario where there is no V2G support, by restricting the number of grid support services per year, the impact on battery health is minimal.

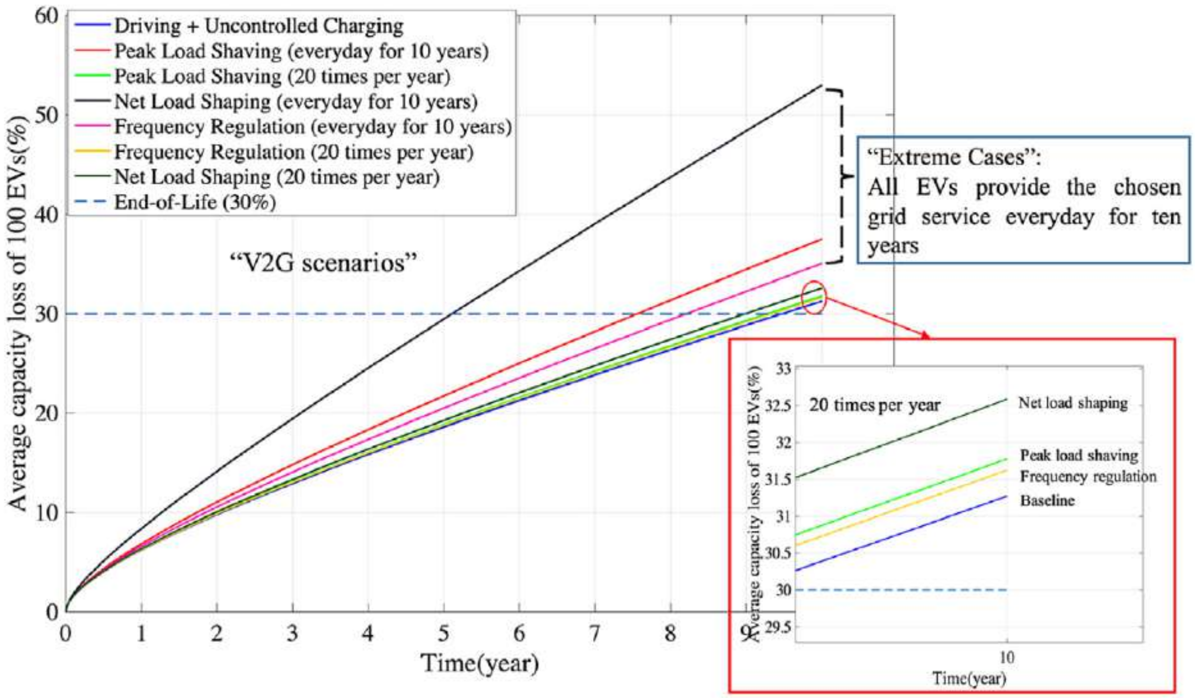


Figure 7.17: Average capacity loss of 100 EVs for performing different grid support services (Dai Wang et al., 2016)

The battery health is measured by its State of Health (SoH), which is a way of accounting for its loss of capacity with time. For example, a battery with initial capacity of 40kWh and SoH of 90% after 2 years means that the effective battery capacity after two years is 36kWh.

7.5 Utilization of EVs for better RE Grid integration

Due to the non-dispatchable nature of RE, its integration with grid introduces several challenges for the TSO in maintaining supply and demand parity. During certain grid operation periods, RE may also need to be curtailed to ensure system stability. As curtailment of RE sources leads to non-optimal operation of grid in terms of economics, so it makes sense to integrate energy storage into the system to facilitate higher RE penetration without the need of curtailment. With added storage, the periods where generation exceeds the demand, the extra generation can just be used for charging the storage and vice versa. The stochastic behaviour of plug-in time of EVs and the SoC level impacts its ability to facilitate RE integration. As per IEA analysis, by 2050 there will 14TWh of EV batteries compared to only 9TWh of stationary batteries (IRENA, 2019).

In theory, EVs with V2G capabilities can facilitate RE integration as they can behave similarly to grid storage facilities. The difference between using EVs and using grid storage is the variable capacity in an EV fleet. Even unidirectional charging can be utilized for RE integration. For unidirectional charging, the EV charging load needs to controlled depending on the RE generation. During peak RE generation periods (such as noon for solar), the EV charging load may be increased so that the RE generation is used to charge the vehicles.

A residential customer with both on-site generation and an EV can improve their self-consumption of energy by using the EV battery as a storage unit to consume their entire generation and only importing the remaining amount from the grid. This approach would give the user the benefit of reduced electricity costs.

Another business model that has gained popularity is EV charging stations with RE sources such as rooftop solar. The charging station has two possible energy sources: their own captive RE resources or RE acquired from the grid. This approach increases the profit margin of the charging station, as it utilizes the low-cost RE sources rather than the higher-priced grid electricity.

7.5.1 Advantages of utilizing RE sources for EV charging

There are several benefits of using RE for the purpose of charging the EV, highlighted below,

1. The goal of transition to EV from ICE vehicles is to reduce the GHG emissions. So use of RE for charging the EVs would further this cause by reducing the energy needed from thermal generating stations.
2. On-site RE sources can help reduce the energy drawn from the grid for EV charging thereby reducing the cost of charging.
3. Local RE sources such as rooftop PV can help in reducing grid congestion as the energy needed for charging EVs can be used from the local RE sources.
4. Use of local RE sources for EV charging would also be beneficial in reducing the bidirectional power flow from these distributed generators (DG) to the grid.
5. With high proliferation of RE sources, especially rooftop PV it has been observed that during periods of high RE generation, the net load of the system decreases significantly making the operation of electrical networks difficult for the transmission system operators and the distribution system operators. As EVs are controllable loads so by aligning EV charging with periods of high RE generation the detrimental impacts of RE generations can also be minimized.
6. As RE sources have started replacing conventional generating units, the requirement of ancillary services has increased in order to maintain grid stability. Using smart

charging of EVs, they can be utilized as resources to supply ancillary services from the demand side.

7.5.2 Scheduling of EV with RE integration

For facilitating the higher usage of RE-based EV charging, different methodologies may be used. The simplest among these methodologies is using a variable electricity price based on the amount of RE generation. By reducing the electricity prices during high RE generation periods, the EV users would be incentivized to charge their EV during these periods of high RE generation. Similar to this, another way of using RE for EV charging is by directly controlling the charging power of the EVSE. As per this strategy, the EV would be allowed to utilize the full rated charging power if there is sufficient RE generation to meet the EV demand. In contrast, the charging power would be reduced during periods of low RE generation. For determining available energy from RE sources, inputs from the energy balancing market would be taken. This solution of RE integration for EV charging has been already commercially deployed in Denmark, as it has one of the highest shares of energy production from RE sources.

The final solution is the active scheduling of the EV charging by the grid operator considering the system state. A detailed description of an EV scheduling algorithm has been described in the case study given below.

Case Study: A scheduling algorithm for adaptive EV charging (Xydas et al., 2016)

In a realistic scenario all the EVs would not agree to having their charging controlled by an external agent, so the demand from the entire fleet of EVs has been segregated into two components: Responsive and Unresponsive. Responsive EV agents have the authority to control the EV charging of their fleet based on the command signals from the dispatcher. In contrast, Unresponsive EV agents cannot control the charging of their EVs, and these behave similar to static loads in the system.

The EV management scheme follows a two-layer decentralized structure. The top layer is the EV/DG aggregator agents at the MV/LV transformer level, while the bottom layer comprises the EV agents at the LV customer level. The EV/DG aggregator agent represents an energy market entity that manages the charging demand of the EV and has installed distributed RE generation in its geographical area. The EV/DG aggregator tries to maximize its profit by providing valley-filling services to the distribution network. Its revenues are also increased when it utilizes its own local renewable energy sources.

The control of the responsive EV agents is done using a dynamic virtual pricing mechanic. The virtual pricing is set depending on the current load and the thermal limits of the feeder. A dynamic structure has been chosen instead of time-of-use tariffs, as it may so happen that during off-peak periods when the electricity price is low, many EVs start charging simultaneously, thereby congesting the grid, as shown in Figure 7.18.

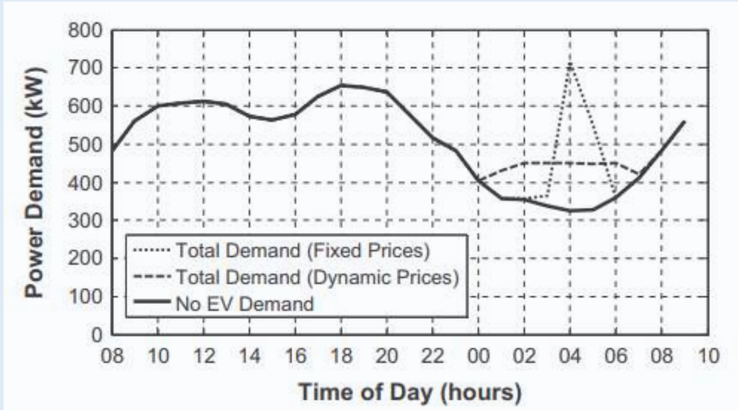


Figure 7.18: Fixed electricity price vs dynamic pricing (Xydas et al., 2016)

The scheduling of charging for the Responsive EV agents is done in six operational phases: *Initial, Forecasting, Planning, Normal, Emergency* and *Final.*

In the *Initial phase*, the EV/DG aggregator decides whether a new forecast for the demand of the unresponsive EV and the renewable generation is required.

The *Forecasting phase* is executed in the first-time step of every 24hr, in which the aggregator forecasts the two-days-ahead demand of Unresponsive EV and renewable generation for every LV feeder of the corresponding MV/LV transformer for each time step. The forecasts, once generated, are added to the demand (without EV), expected to be provided by the distribution network operator for every LV feeder. If the day is divided into N units, then for every feeder, the total scheduled demand is given as

$$T_{sch_{demand}}^{k,f} = F_{UnresponsEV}^{k,f} - F_{DER}^{k,f} + S_{RespEV}^{k,f} + F_{noEV}^{k,f}$$

where,

k=1,...N

f=1,... number of LV feeders connected to the MV/LV transformer

$F_{UnresponsEV}^{k,f}$ is the forecasted charging demand from the Unresponsive EV fleet

$F_{DER}^{k,f}$ is the forecasted RE generation

$S_{RespEV}^{k,f}$is the total scheduled charging demand of the Responsive EV

$F_{noEV}^{k,f}$ is the forecasted demand without EV or RE.

Based on the total demand the N virtual prices ($VP_{k,f}$)were calculated. These virtual prices were modelled to control the EV charging for the valley filling purposes. The EV/DG aggregator decreases the virtual price during periods with low demand, thus incentivizing the EV agents to charge accordingly. If there are new arrivals of the EV agents, the agents enter in the *Planning phase.* In this phase a queue is created containing all the EV agents that are connected to the charging stations and the schedule problem is solved on a first come first-served sequence according to the virtual prices sent from the EV/DG aggregator. The schedule for each EV agent is determined by minimizing the objective function given below,

$$\min \sum_{t_n}^{(t_n+d_n)} P_n(t).VP_{k,f}(t)$$

Subject to constraints,

$$\sum_{t_n}^{(t_n+d_n)} P_n(t) = \frac{(SOC_{final_n} - SOC_{in_n})C_{batt_n}}{\delta_{eff_n}}$$

$$P_n(t) \leq P_{ch_{nom}}$$

Once the EV agent defines its charging schedule, it informs the EV/DG aggregator and leaves the Schedule Queue. Once the EV/DG aggregator receives a charging schedule it recomputes the total schedule demand and adjusts the virtual prices accordingly. This sequential update of virtual price has the advantage that the feeder is not overloaded due to simultaneous charging of multiple EVs during low electricity price periods.

After all the EV agents participate in the planning phase, the *Normal phase* starts. In this phase, the EV/DG aggregator monitors the No EV load, the demand from Unresponsive EV, scheduled Responsive EV demand, RE generation and checks for possible violations of the network technical constraints. . In case there are no violations, the EV agents execute their charging schedule for the current time step. However, if the technical constraints are violated, the charging schedule is not executed, and the *Emergency phase* begins. In this phase, the charging of the responsive EV agents is rescheduled by the EV/DG aggregator to avoid technical constraint violations. During the *Final Phase*, the current time step is compared to the scheduled disconnection of EV, and subsequently, the EVs are disconnected accordingly.

The flowchart for the complete scheduling process is given in Figure 7.19.

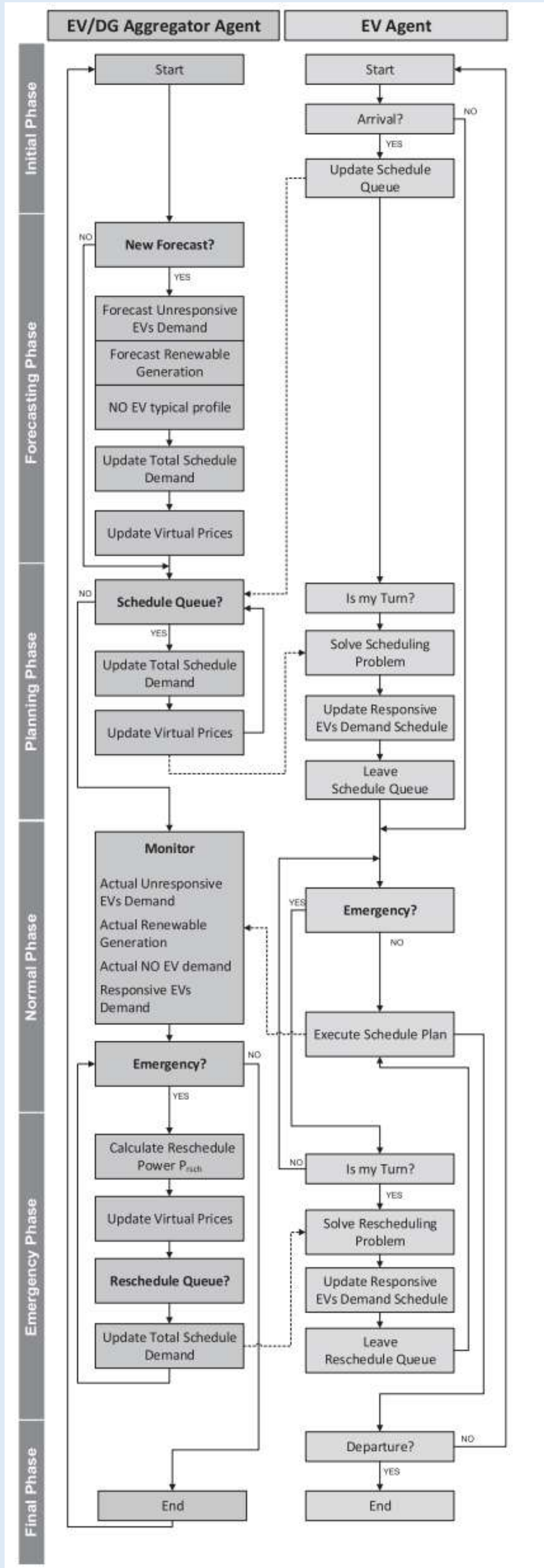


Figure 7.19: Flow Chart of the complete methodology (Xydas et al., 2016)

The above methodology is then implemented to study the impact of EV charging on the UK distribution network considered 4 LV feeders and 640 total EVs. The solar park of 132kW was also connected to the distribution feeder. The results for the case study have been shown in Figure 7.20.

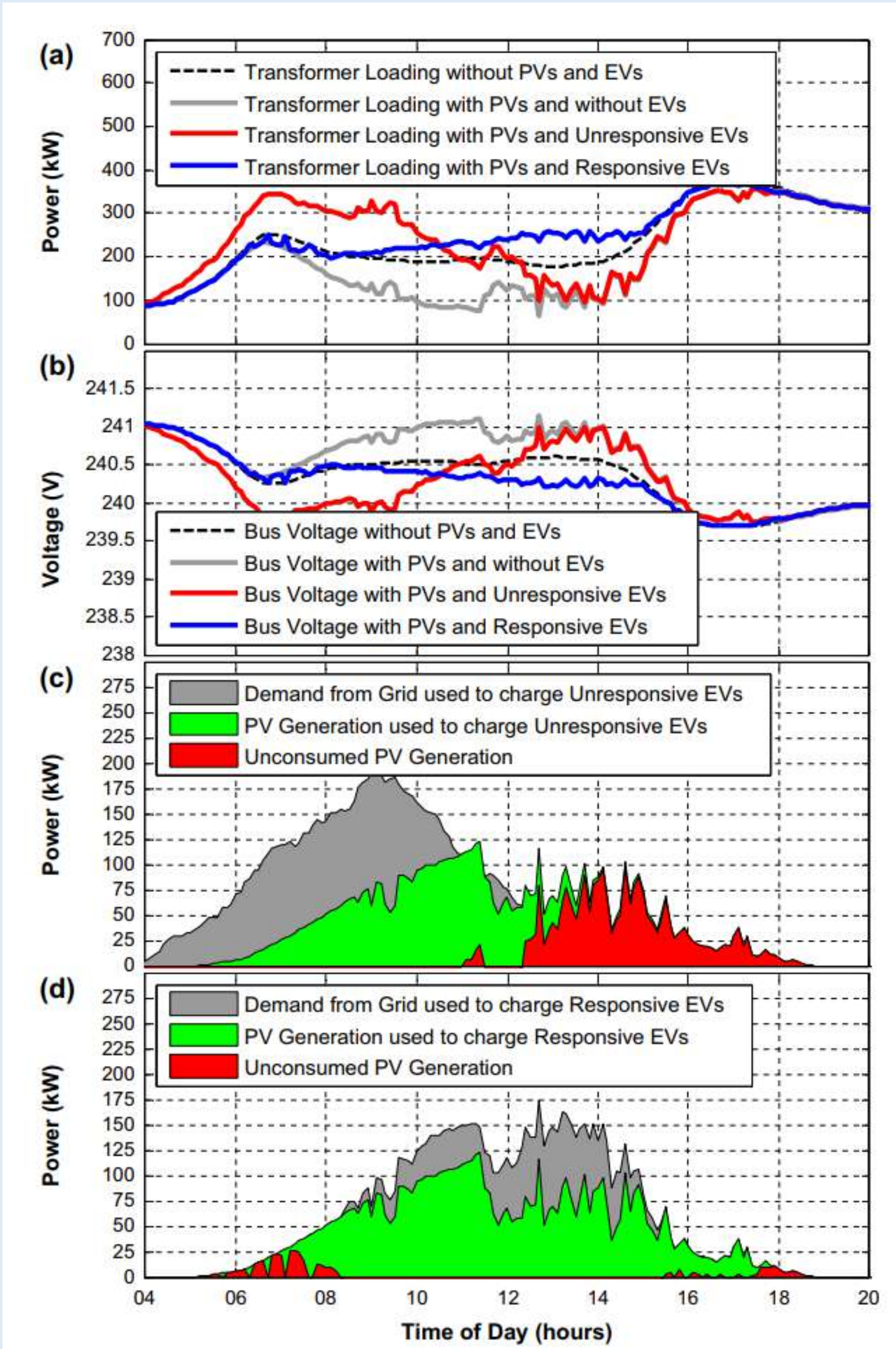


Figure 7.20: (a) Power demand for the MV/LV transformer, (b) Voltage profile at the LV bus level, (c) Charging demand from the Unresponsive EV and (d) Charging demand from the Responsive EV agents (Xydas et al., 2016)

As can be seen from Figure 7.20(a) and (b), in case where PVs and Unresponsive EVs were considered, a new peak was created during the morning, which was mitigated by using the Responsive EVs. Similarly, the voltage fluctuations have also been reduced by using the Responsive EVs. Figure 7.20(c) and (d) shows that the Responsive EVs were also able to consume the energy generated from the RE source to a higher extent as compared to the Unresponsive EVs.

7.5.3 Cost comparative analysis of RE based charging stations

To check whether keeping RE sources and Battery energy storage systems (BESS) systems in EV charging stations is techno-economically feasible, it necessitates comparative cost analysis between EV charging infrastructure being supplied power only from the utility and from the utility and RE sources. In this scenario, a study on utility costs savings for EV charging infrastructure has been done by National Renewable Energy Laboratory (NREL), the U.S., where the lifecycle costs have been compared considering an operational life of 25 years (Elgqvist & Pohl, 2019). Scenario 1 is when all electricity for EV charging is purchased from the utility. In contrast, in scenario 2 electricity required for EV charging is supplied from PV and stationary storage and remaining required energy is purchased from the grid. The EV charging profile vs PV output has been shown in Figure 7.21. Clearly, some parts of the EV loads can be supported by PV output.

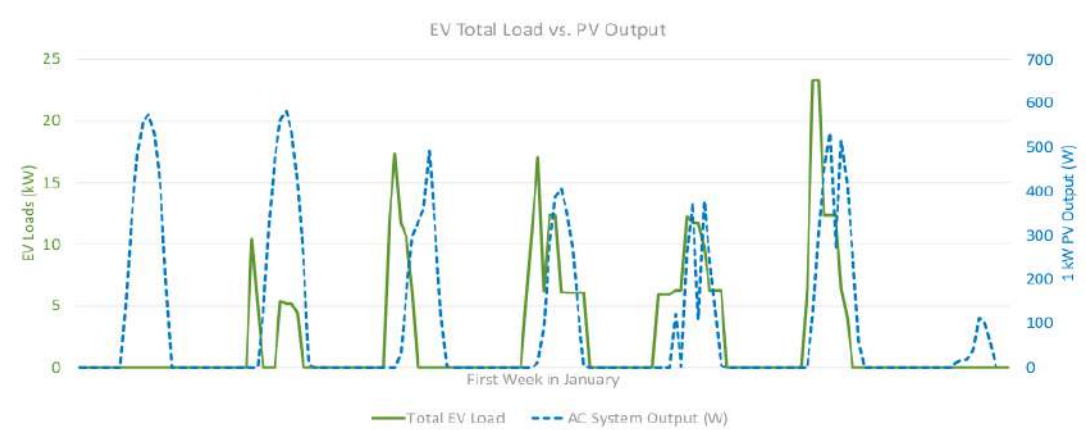


Figure 7.21: EV total load vs. PV output **(Elgqvist & Pohl, 2019)**

The charges for connection to the grid have been given in Table 7.2.

Table 7.2: Charges for grid connection **(Elgqvist & Pohl, 2019)**

	INR/kWh	INR/kW	INR/month
Customer charge			1911.54
Demand charge		798.46 (Oct – May) 1136.93 (Jun. – Sept.)	
Energy Charge	2.61		
Fuel adjustment factor	2		
Total	**4.61**	**798.46 (Oct – May)** **1136.93 (Jun. – Sept.)**	**1911.54**

Besides, few necessary assumptions are considered for the study which have been provided in Table 7.3.

Table 7.3: Assumptions **(Elgqvist & Pohl, 2019)**

Input	Assumption
Technologies	EV, solar PV, battery storage (depending on scenario)
Objective	Minimize lifecycle cost (cost-effective projects)
Ownership model	3rd party financed
Analysis period	25 years
Discount rate	3% for site/8.1% for developer
Escalation rate	2.60% per EIA utility cost escalation rates
Inflation rate	2.1% per Energy Information Administration (EIA)
Incentives	30% solar investment tax credit (ITC); 5 year Modified Accelerated Cost Recovery System (MACRS) for PV & storage (storage not charging from grid)
Net metering	None
Electricity sellback rate	INR 0/kWh
Interconnection limit	None
Technology costs	PV: INR 149.11/W (EUR 1.69/W) ground mount installed; INR 1,155.57/kW/yr (EUR 13.12/kW/yr). O & M storage: INR 37,276.53/kWh (EUR 423.21/kWh) and INR 74,553.05/kW (EUR 846.42/kW); replacement costs in year 10: INR 17,147.20/kWh (EUR 194.67/kWh) and INR 34,294.40/kW (EUR 389.35/kW)
Technology resource	TMY3 Weather Data
Area for PV	Not constrained

In case of scenario 2, the capital cost will be higher than scenario 1 but the lesser running cost will pay back the revenue after a specific period of time. To be beneficial, this payback period should be less than life-span of the RE and storage equipment. The result of NREL study has been presented in Table 7.4

Table 7.4: Cost comparison **(Elgqvist & Pohl, 2019)**

Scenario	EV chargers only (Scenario 1)	EV chargers +PV and storage (Scenario 2)
PV size (kW)	0	9
Battery size (kW)	0	17
Battery size (kWh)	0	28
Total capital cost (INR)	0	36,60,554
Electricity purchases (kWh)	17,400	9,100

Percent RE (%)	0	64
Year 1 energy cost (INR)	82,008	44,731
Year 1 demand cost (INR)	3,35,488	1,49,106
Year 1 fixed cost (INR)	22,365	22,365
Year 1 total electricity cost (INR)	4,39,863	2,16,202
25 year lifecycle cost (INR)	1,04,37,427	87,97,259

It can be observed that in scenario 2, although the total capital cost is INR 36,60,554 (EUR 41,559) the annual required electricity purchases from the utility has been reduced to 9,100 kWh from 17,400 kWh in scenario 1. Consequently, 1st year total electricity cost has been significantly decreased. Finally, over 25 years, the lifecycle cost of scenario 2 works out to be lesser than scenario 1.

The cost for EV charging can be further reduced by co-locating EV chargers with building loads. In this scenario, NREL installed the EV chargers in the existing building connection without a separate meter. The peak load of the building and the EV charging demand do not coincide, so there was no requirement for a separate power connection. This reduced the demand charges thereby reducing the net electricity bill as given in Table 7.5.

Table 7.5: Potential savings of co-locating EV charging infrastructure with a commercial building**(Elgqvist & Pohl, 2019)**

Scenario	EV Chargers only	Building only	Building+ EV Chargers (Separate meters)	Building+ EV chargers (Combined meter)	Building + EV Chargers (Combined Meter) Add PV + Storage
PV size (kW)	0	0	0	0	155
Battery size (kW)	0	0	0	0	66
Battery size (kWh)	0	0	0	0	77
Total capital cost (INR)	0	0	0	0	3,10,29,825
Electricity purchases (kWh)	17,400	1,022,700	1,040,100	1,040,100	852,100
Percent RE (%)	0	0	0	0	19
Year 1 energy cost (INR)	82,030	47,05`,556	47,87,586	47,87,586	39,22,540

Year 1 demand cost (INR)	3,35,578	31,99,182	35,34,760	32,58,840	26,17,512
Year 1 fixed cost (INR)	22,372	22,372	44,744	22,372	22,372
Year 1 total electricity cost (INR)	4,39,981	79,34,567	83,67,090	80,68,798	65,62,424
25 year lifecycle cost (INR)	1,04,40,220	18,85,95,117	19,90,35,337	19,18,76,329	18,59,85,062

Chapter 8: Smart Charging

An increasing adoption rate of electric vehicles due to socio-environmental benefits and attractive governmental policies has encouraged EV penetration into the grid. Refuelling an electric vehicle via recharging the battery using conventional charging practices with household facilities is termed dumb charging. It is an uncontrolled type of charging that facilitates a plug-and-charge mechanism. Significant EV integration using dumb charging negatively impacts the grid. Uncontrolled and plug-and-charge mechanism creates high peak loading issue. This high peak loading issue initiates a new challenge of maintaining generation-demand balance at peak loading time. It necessitates scheduling of expensive generators and the requirement of installation of new generation plants. This solution for the high peak loading issue is not economically and environmentally viable because it is expensive and at the same time conventional generation sources are filling the requirement of providing the additional power. The addition of conventional generators will cause a simple shift in utilization of non-renewable fuels and emission of hazardous gases. High demand and plug-and-charge mechanism are also associated with the uncertain loading, and it requires more backup storage. Uncontrolled charging of EVs extracts a huge amount of power which results in network overloading conditions. Network overloading condition includes overloading of equipment, faster aging of devices leading to frequent occurrence of faults and in extreme case may lead to system instability. Equipment stressing and faster aging results into requirement of major upgradation and reconfiguration. Higher extraction of supply power from EV centric regions and simultaneous EV charging creates power line congestions. It can lead to instability and blackouts. All the above stated drawbacks of uncontrolled EV charging can be addressed by utilizing smart charging. Smart charging mitigates the drawback and limitation of dumb charging and facilities additional advantages of maximizing the utilization of renewable generations, support ancillary services and provide backup storage.

In smart charging, EV is charged considering all the decision parameters of the system and requirements of EV owner. An external entity or a person controls the charging and decides the schedule of charging complying the interests of EV owner. In other words, smart charging is an action of externally controlling the EV charging for predefined objectives and constraints. As smart charging is externally controlled so it requires observability and communication between the entities. EV owner and system operator are two basic stakeholders in smart charging. Both the stakeholders have different objectives to perform and participate in smart charging. System operators encourage smart charging to maintain the grid stability whereas

EV owner is focused on reducing the EV charging cost. System operator is a central entity and in practical implementation of smart charging it is very difficult to manage connection between system operator and an individual EV owner. To resolve this, an aggregator the third stakeholder of smart charging is introduced in the system. Role of the aggregator is to establish an indirect connection by coordinating with EV and system operator, it acts as a middle entity between EV owner and system operator. It collects information from both (viz, system operator and EV owner) and take suitable decision on EV charging considering the request and constraint from both the parties. Aggregator also has its objective of profit maximization.

Smart charging depends on objective and constraint to be maintained at every time slot. The objective of smart charging varies according to stakeholders and their requirements. Overall system cost minimization, load levelling and valley filling, maximization of RE utilization, and providing grid support services are the major objectives of system operator. Minimization of charging cost, maximization of satisfaction factor, and load levelling are the common objectives from EV owner's perspective. Smart charging is performed using different strategies which are the combination of information flow and decision taking ability between aggregator and EV owner. Based on the information flow and decision taking smart charging is categorized into different strategies as shown in Figure 8.1.

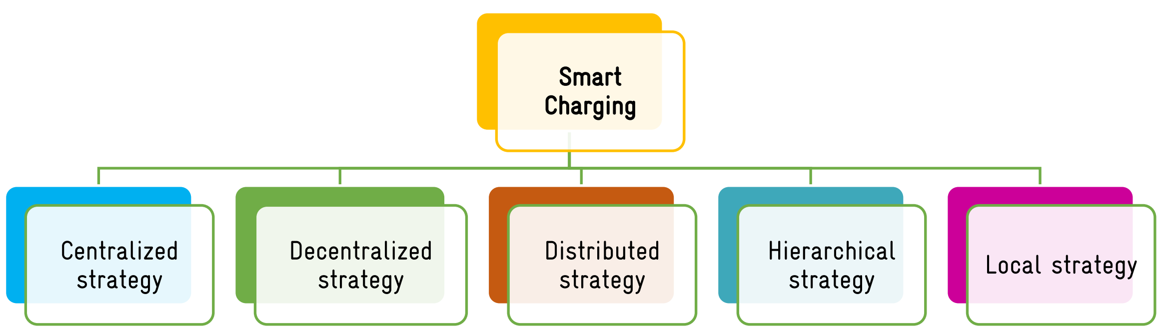


Figure 8.1: Smart charging strategies based on control architecture

In centralized strategy information signal viz, power request from EVs is passed to an aggregator and aggregator decides on scheduling, considering the system constraints. Here, the decision is taken by aggregator and communicated to an EV. In contrast to it, EV owners take charging decision while aggregator tries to influence the charging behaviour of EV owner by varying the electricity prices. In extension, in decentralized strategy, a group of aggregators working in decentralized manner is communicating within themselves to take optimal pricing decisions. All the above strategies are working majorly towards single objective belonging to a stakeholder. In actual EV charging environment, all the stakeholder wishes to achieve their objective. In accordance with this situation, hierarchical strategy allows each stakeholder in every level to achieve their objectives. The strategy is further categorized based on various combination of centralized and decentralized method of decision taking between levels. Apart from all the above aggregator dependent strategies, one aggregator independent strategy is also present. In this EV owner takes strategical charging decision considering local parameters to achieve the desired objective.

Smart charging strategy, dependent on electricity price is called as time-of-use tariff structure. In this method, different electricity prices are applicable according to load and generation availability in the system. Using time-of-use tariff, the grid operator tries to influence the EV owners to shift their EV charging to an off-peak period such that the load is levelled. The customers are attracted towards time of use tariffs as they can potentially reduce their charging costs, by shifting their charging to off-peak periods. Smart charging output is influenced by implementation method and objective. Different implementation methods such as deterministic methods, heuristic methods, artificial intelligence-based methods, and GAME theory-based methods are used for smart charging. According to the nature of optimization of charging problem, an appropriate method can be adopted. Linear optimization, convex optimization, Mixed Integer linear programming (MILP), and non-cooperative GAME theory are the commonly used methods used for smart charging implementation. Objective function of an optimization problem influences the charging schedule in a smart charging.

Communication and computational power are the major requirements for implementing smart charging in EV ecosystem. The smart charging strategies given in Fig 1 has different communication and computational requirements which effects applicability of smart charging. Centralized strategy requires higher bandwidth communication to avoid delay in the charging process, whereas decentralized and distributed strategy requires medium bandwidth communication. Local strategy has lower requirement of high bandwidth communication. Based on computational aspect centralized strategy requires highest computational power due to central controlling whereas decentralized strategy distributes computation requirement to the subordinate level of EVs.

In actual practice smart charging mainly depends on type of connector present in the charger. There are different connectors available in the market. According to smart charging requirement connectors is classified as connectors without control pilot pin and connector with control pilot pin. Although both types of connectors can perform smart charging, connectors with control pilot pin are able to pass modulated charging signal as a result of optimization problem and have finer alterations of charging power, while connector without control pilot pin can perform smart charging using simple on/off functionality based on ToU tariffs.

Chapter 9: Cybersecurity for Smart EV Charging

Smart EV chargers are susceptible to cyber-attacks as already reported by Kaspersky Labs, who revealed flaws in the security of ChargePoint Home's smart phone application for EV charging. This security flaw could potentially enable a remote attacker to remotely access the charger and tamper with the charging (Kaspersky, 2018). The EV ecosystem is a multi-layer cyber physical system with multiple different communication routes and interfaces as shown in Figure 9.1 (Acharya, Dvorkin, Pandzic, et al., 2020).

9.1 Physical Layer

The physical layer of an EV ecosystem include the components such as battery units, power conditioning units, motors, filters, protective systems, charger connectors, etc. These are physical devices that provide different functionalities to the EV ecosystem. These physical layers communicate with each other using the cyber layer.

9.2 Cyber layer

The cyber layer includes the in-vehicle layers as well as the external EV-X (X can be EVCS, DSO, road infrastructure etc.) layers.

9.2.1 In-vehicle layer

Most EVs have over 125 electronic control units (ECUs), which enable the control of different components of the vehicle such as braking, battery management, infotainment etc. Each ECU consists of a microprocessor, a memory and input/output interfaces. The ECUs are connected via the controller area network (CAN), local interconnected networks (LINs), media-oriented systems transport (MOST) and FlexRay as shown in Figure 9.1. Out of these different networks, the CAN is probably the most crucial, as with the CAN network the EV charging can be tempered with.

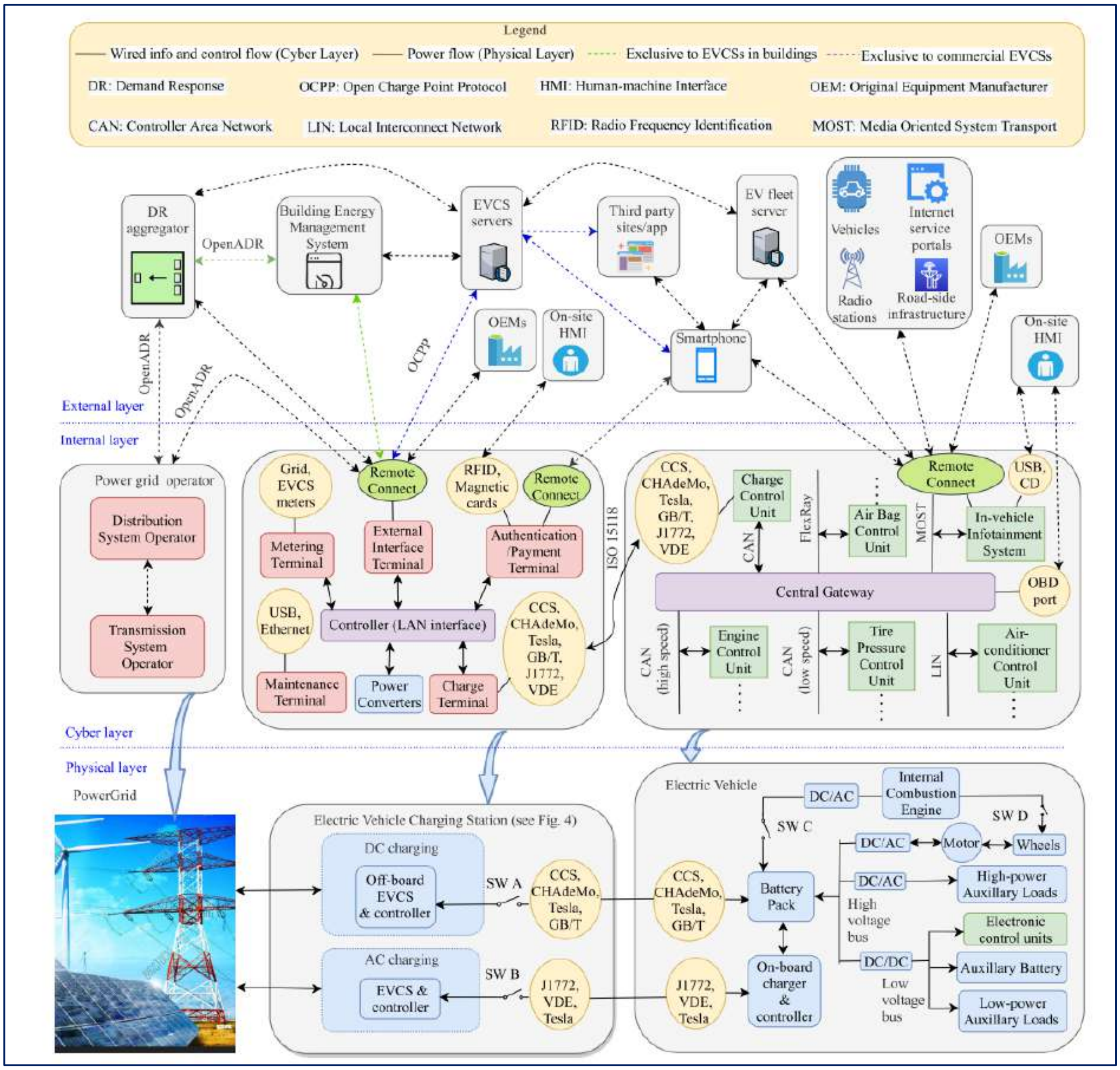


Figure 9.1: Schematic diagram of the cyber physical nexus of EVs, EVCSs and the power grid (Acharya, Dvorkin, Pandzic, et al., 2020)

The LIN is used for ECUs such as air-conditioning, MOST is used for in-vehicle infotainment system, and it requires a high bandwidth communication. The FlexRay is used to control ECUs such as air bag control unit.

9.2.2 EV-EVCS

To coordinate charging details and set up preferences like charging current and voltage levels, EVs communicate with EVSE. Level 1 and Level 2 charging typically use a pilot wire for this communication, while Level 3 EVCS communicates using the CAN or PLC protocol. The commands transmitted include the readiness of the EV to accept charging power and the EVCS of supplying the charging power, the charging current requirement, the SoC of EV battery as well as ground fault detection.

9.2.3 EV-Physically Accessible Ports

EVs come equipped with USB ports, compact disk (CD) slots, SD card slot and OBD2 port for external communication. Although most of these ports are used for infotainment purpose, the OBD2 port is a standardized interface to the CAN bus that is used generally by the mechanics or other regulatory authority to get information about the status of the EV.

9.2.4 EV-Positioning Satellites

Most modern vehicles also come equipped with GPS, for use in navigation systems.

9.2.5 EV-OEMs/Vendors

The EVs also regularly communicate with the OEMs for regular software updates and patches using wide area network (WAN) such as cellular network. The OEMs prefer wireless patching strategies rather than via human machine interfaces (HMI) like USB or ethernet ports because of swift delivery as well as cost effectiveness.

9.2.6 EV-Road Side Infrastructure and Vehicles

Modern EVs also have the capability to communicate with roadside infrastructure or even with other vehicles mainly for automated and self-driving vehicles.

9.2.7 EVCS-Onsite HMI

EVCS come equipped with HMI such as touchscreen, card readers and other ports for authentication and maintenance. These interfaces are used for different functions such as customization of the charging session, payment method, duration of charging process etc. The displays also show the real-time information of the EVCS including the details of the charging session. The card reader is an authentication tool of the user and payment of the charging session. Radio frequency identification (RFID) cards and smartphone applications are two of the most common methods of authentication. For maintenance purposes the EVCS are equipped with Universal serial bus (USB), serial and ethernet ports.

9.2.8 EVCS-Building Energy Management System(BEMS), Power Grid Interface

The participation of EVCS in DR services involves two-way communication, where the grid or aggregator broadcasts the DR schedules and price signals to each individual EVCS while acquiring the real time energy usage. The communication from the grid or aggregator can be either directly to the EVCS or routed via BEMS. This communication is performed via the open communication protocol, OpenADR 2.0 specification.

9.2.9 EVCS-EVCS Servers, Smartphone Interface

EVCS operated by the same operator are generally networked via a centralized server. There are four major functions of the centralized EVCS server,

- Congregate and archive real-time measurements of each EVCS
- Authorize EVs to charge remotely.
- Broadcasting of availability of EVSE, the prices for charging, connector types available to a web-based or smartphone application.
- Relay information between power grid operator and the energy management system.

9.2.10 EVCS-OEMs, Vendors

Similar to communication between EV-OEM, the EVCS also communicates with its OEM for regular software updates and security updates.

9.3 Classification of Cyber Attacks

Cyber-attacks are categorized using the STRIDE threat model. The different components of the STRIDE model have been discussed below,

9.3.1 Spoofing

The disguising of a legitimate source or process is referred to as spoofing. For example, the 2015 Ukraine power grid attack was caused by this class of attack in which phishing emails were sent to the employees to access the SCADA system.

9.3.2 Tampering

The destruction or unauthorized alteration of data or process is termed as tampering. This kind of attacks are more prevalent to system which deal with larger volumes of data transfer such as data measured by the SCADA units can be tampered with to create malicious control signals.

9.3.3 Repudiation

Repudiation attack occurs when the user denies the fact that they have performed a certain action or has initiated any form of transaction. This form of attack is likely to occur in services such as demand response in which different load agents can participate.

9.3.4 Information Disclosure

The unauthorized acquisition and dissemination of information comprises of this form of cyber-attack.

9.3.5 Denial of Service (DoS)

If an authorized entity is deprived of reliable and timely access to services and information, then this class of cyber-attacks are termed as DoS attacks. This attack is likely to be combined with information disclosure and tampering attacks.

9.4 Vulnerabilities to Cyber attacks

9.4.1 In-vehicle vulnerabilities

The CAN bus architecture is a peer-to-peer system, the CAN architecture is not immune to malware. By having access to the CAN bus or certain electronic control units (ECU's) an attacker can completely control the EV operations, which means they can modify, eavesdrop, reverse engineer or spoof with a malicious intent as the message sent by an ECU or any peripheral device through the CAN bus is received by all of its peers. Also, the message transmitted via CAN is neither encrypted nor authenticated which makes them vulnerable to cyber-attacks.

9.4.2 EV-EVCS vulnerabilities

An EV communicates with the EVCS via a wired communication layer such as CAN or PLC using protocol ISO 15118. Although ISO 15118 regulates the communication, it lacks security measures like encryption and message certification. This can enable a remote attacker to eavesdrop, spoof or modify the EV charging message.

9.4.3 EVCS internal vulnerabilities

The RS232 protocol is used by EVCS internal processors to communicate using LAN. When an EVCS loses communication with its server, the OCPP gives the EVCS the authority to authenticate EVs by itself, which forces the EVCS to store the authentication database locally. So, if an attacker gains access to the EVCS, he also acquires the information of locally charged EVs in the past.

9.4.4 EVCS-On-site HMI vulnerabilities

Public EVCS are equipped with different interfaces for interaction with the EVCS, which makes them easy targets for cyber-attacks. The USB ports behave as convenient access points which may allow the attackers easy access to copy EVCS configurations, modify or erase data, or access EVCS server authentication credentials. By placing phishing RFID card readers alongside an EVCS, the attacker can gather the user login credentials stored in the RFID cards.

9.4.5 EVCS-EVCS server vulnerabilities

OCPP protocol is generally utilized for communication between EVCS and EVCS servers, which is vulnerable to man-in-the-middle cyber-attacks on data privacy and message authenticity due to lack of server/client certificates and end to end message encryption. These vulnerabilities allow for stealing, altering, and spoofing of EV charging data. The recent release of OCPP 2.0.1 launched in April 2020, has however enhanced the security features with authentication and client-side-certification

9.5 Threat to Power Grid

A cyber-attack on the operation of EVCS may be executed with an intent of harming the power grid. EV chargers at public spaces are susceptible to two forms of cyber-attacks, i) DoS of EVCS and ii) EVCS data tampering. The cyber-attack tree for a power grid threat by exploiting the vulnerabilities of EV and EVCS is presented in Figure 9.2. The goal of the attack is to create a voltage or frequency instability event in the grid which could trigger the protective relays and thereby lead to a cascade of failures.

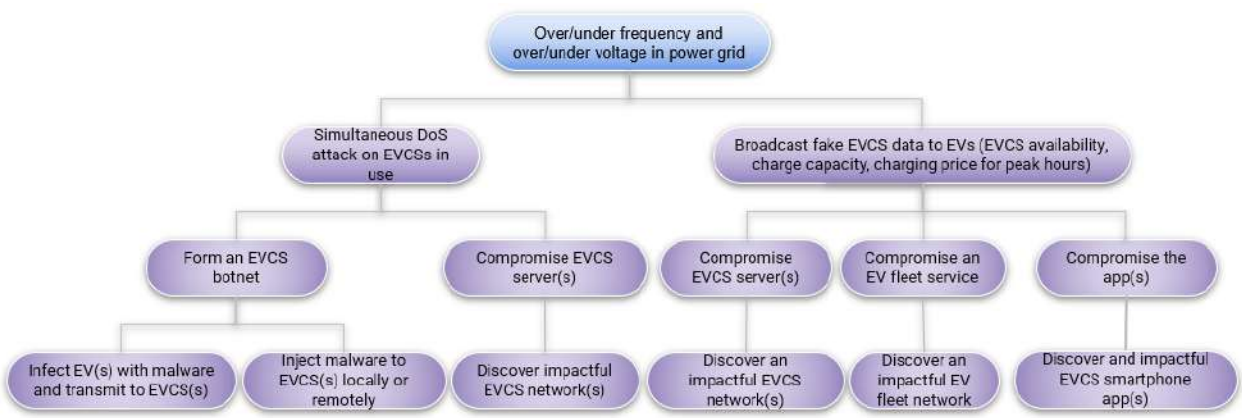


Figure 9.2: Cyber-attack tree for over/under frequency and over/under voltage events in power grid using EV and EVCS vulnerabilities **(Acharya et al., 2020)**

In case of DoS attacks, the attacker would shut down the operation for a bulk of EVCS, thus significantly reducing the load in the system which can create over frequency events. For this to happen the attacker either needs to form an EVCS botnet (a botnet is a network of equipment that have all been attacked by a single attacker) or compromise an EVCS server. In order to create a significant change in system load the attacker needs to compromise a sufficient number of EVCS at their peak operating time.

In case of tampering attacks, the attacker changes the EVCS information shown on the webpages or smartphone apps as unavailable or display high charging prices. This leads to routing of EV charging to a different location where the added demand may cause stress on the power system. Here, the goal of the attacker is to overload the grid equipment in a chosen location, thus causing voltage failures and other cascading events. For e.g., the authors in (Acharya, Dvorkin, & Karri, 2020) acquired the details of all commercial Level 2 and Level 3 EVCS in Manhattan, New York and demonstrated that by compromising the demand of 1000 EVCS charging at 350kW each, could trigger over frequency relay operation, leading to major power outages.

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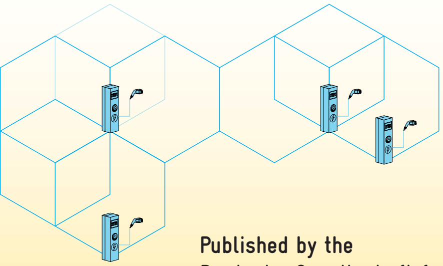

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