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Analysis on the effect of different charging standards on the charging process

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Research work
for
Mr. Jabroot Sarkhel

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Title: Analysis on the effect of different charging standards on the charging process

Analyse der Auswirkungen von verschiedenen Ladestandards auf den Ladevorgang

Research question: Are there any differences between the US standard compared to the European standard regarding the charging process?

The thesis has to contain the following aspects:

1. Research about
    a. What are the charging standards in Europe?
    b. What are the charging standards in the USA?
    c. What are the differences and how might they affect a charging process?
2. Setting up a model in Simulink
    a. Model of an European and USA charging station
    b. Model of an HV battery for further investigations
3. Generation of test and investigation scenarios
    a. Possible cases are short circuit and load dump
    b. Extension of this list in consultation with me
4. Deduction on possible problems which need to be considered in early stages in the development

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Second, I am eternally indebted to my fiancée Quinta, my father Suleman, my mother Josephine, my two sisters Samrugh and Samruth, and very close friends. Their love, emotional support, and belief in me during the course of my studies have kept me going. In the very difficult moments, it was their unshakeable support that brought back memories of why I started in the first place. Were it not for them, I would have quit a long time ago.

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Abstract

This thesis core structure revolves around electric vehicle charging and charging infrastructure, especially the standards provided by the regulatory bodies in US and EU concerning it. Typically, when EV charging system is considered, it consists of charging point, a coupler/connector, on-board/off-board charger, and a battery pack that is charged via the charging station, and the standards provide a proper management and control system depending on the region or country to ensure proper communication between the EV and EV supply equipment (EVSE), also keeping in mind the safety/protection.

To be precise, following are the topics that are discussed in this paper:

- Charging: General idea behind EV batteries, terminology, charging strategies, connection between EV and EVSE, charging system and classification.
- Charging Station: General idea behind the components used in a charging station and types of charging stations (AC/DC).
- EV charger classification: Classification criteria, types of charger used, single/dual charger, reliability of a charger and impact of charger on the utility grid.
- Charging Standards used in Europe and USA, differences between them and how they might affect the charging process.
- Development of DC Fast Charging System and High Voltage Battery, working on the standard and communication based model.
- Analysis of the faulted conditions mentioned by the standards i.e., short circuit and load dump theoretically and practically through the developed model.
- Near to the future development phase considerations.

1 Introduction

1.1 Background

With continuous growth, development and industrial revolution, the amount of vehicles on road have been increasing worldwide. Transportation has overtaken the industrial sector as the the biggest energy consumer. Nonetheless, the vehicles also appear to be one of the biggest contributors of the CO_2 as well as air pollution throughout the world[7, 22]. Considering the statistics of Europe, the total share of EU greenhouse gas (GHG) emission for road vehicles is around 20.4% [9]. According to a survey, only 21.4% of the vehicles concluded in fuel saving against higher initial investment costs [37, 50]. One of the possible ways to reduce GHGs and air pollution is electrification of the transportation and this development has been on the rise since the past two decades with huge investments and innovation coming in.

In comparison to ICE Vehicles, EVs are highly efficient, better performing, have considerably lower driving cost per mile and much higher tank-to-wheel efficiency [35] as depicted in Figure 1.1.

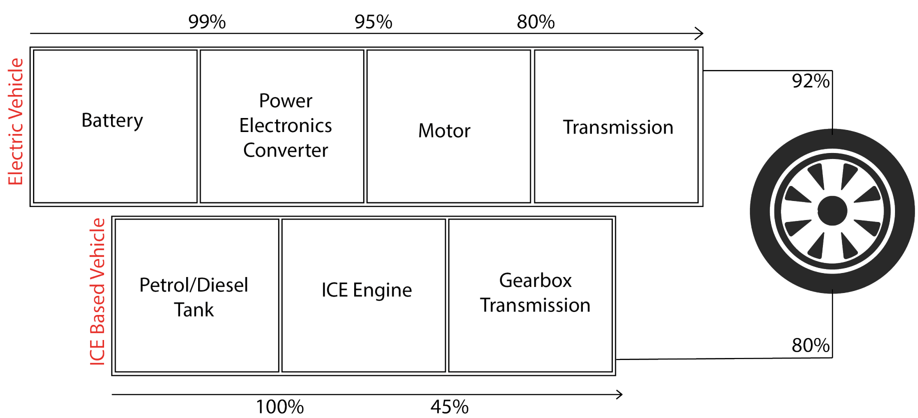


Figure 1.1: Efficiency comparison between EV & ICE Vehicles

Considering all these advantages of the EVs over ICE vehicles, the question still arises, *why majority of the people still consider ICE vehicles over EVs?* The number one objective is the on-board energy storage system (ESS) of EV should meet equivalent energy demands as of the ICE vehicles. Past research suggested that the energy density of EV is 200-300 Wh/kg which when compared to ICE that has energy density of 13,000 Wh/kg is low[35]. Also, majority of the people have 'range anxiety' since EV range is limited to it's complete charge of the battery[35].

Considering the other perspective, Electric vehicles require charging infrastructure that has to meet similar objectives as that of the existing refueling stations. Charging the vehicles at public charging stations still requires 30 minutes to 1 hour considering fast DC charge, while the infrastructure affects negatively the utility grid when there is high load demand[35]. Recent research and development have shown promising results which are discussed in our thesis paper further in the upcoming chapters.

1.2 Market Perspective of EVs

In terms of market, EVs growth on road has been increasing greatly since 2010, it surpassed 5.1 million in 2018, while the worldwide EV fleet including light duty vehicles stood at 7.5 million, considering 2020, the fleet went over 10 million and in 2021, EV sales hit a new high, bringing the overall EVs on road to around 16.5 million[49]. More than 85% of the overall worldwide EV sales in 2021 came from China and then Europe, where it reached 630,000 EVs, while in US had a share of 10% in total[49].

Considering European statistics, according to the data provided by the European Automobile Manufacturers Association (ACEA) is that the EVs are gaining more and more popularity around Europe[15]. The numbers suggest that EV registration increased from 5.9% (2019) to 37.6% (2021). And also, there is a general decrease of ICE vehicles from 36.7% to 19.6% (Petrol) and 55.6% to 40% (Diesel)[15, 16]. Also, considering the EVs promising technology and efficiency performance, US and UK have 0.9% to 1.4% EV sales, during the initial stages of EV market. According to IEA, EV sales have increased exponentially i.e., in 2016, 2 million EVs sold, 40 million in 2020, and 70 million projected for the year 2025[51].

1.3 Future Predictions for EVs & their Infrastructure

The conventional transportation system is found to impact the environment greatly with high level of pollution in the recent years, therefore it is necessary to consider an alternative technology that could lower the CO_2 levels and be beneficial for the upcoming generations.

In the upcoming years, the improvements and further research on EVs and their infrastructure would be beneficial to decrease the pollution especially when considering the transportation sector with an increased market of around 72.9% [50]. Along with that, depending on the regions and their grid utilization, standards are developed and continuously being improved to achieve a better integration of the EVs in to the environment, also keeping in mind other aspects i.e., financial, cultural, social and environmental. Even though government and companies around the world are on the verge on developing optimized standards, strategies and policies, the market share of EVs still has a lot to do and for that government policies and regulations need to be attractive and in favour of the users.

Infrastructure, i.e., the core of the EVs needs to be strongly developed and arranged in order to reduce customers ’range anxiety’. Policymakers are developing policies considering fast charging infrastructure that is a critical point for regular usage of EVs especially when put in to comparison with the fuel-stations. Main idea should be that the infrastructure should be allocated in most of the densely populated area[37], also improving and optimizing geographical location in order to reduce range concern. Charging arrangement should be flexible in order to encourage new charging techniques. Considering government’s policies and regulatory bodies, incentives should be introduced, i.e., discounts, tax reduction, free toll pass and bus lane access facilities etc [33], that are already incorporated in to European market.

by 2040, in comparison with 2016, the number of EVs on road would increase by a factor of 70 which of course depends on the rapid optimization of the EV technology, cost reduction and government incentives, increasing the EVs share of the global road transport fleet to 11-28%, much higher than 2016 figures[5]. Also, improvements in the battery pack should be considered as well i.e., compactness, better integration, faster charging times, better thermal management system (TMS) and optimizes enerygy storage system (ESS). Charging stations could be equipped with solar panels for on-site electricity generation, reducing excess load on utility grids especially during high load demands. Increasing the battery capacity would increase the range, while also working on faster charging to reduce waiting times. More efficient TMS would result in much more improved motors with bigger and compact batteries.These advancements are crucial in order to compete with the conventional ICE vehicles and could potentially lead to higher adoption of the EVs and also increase competition between the service providers and manufacturers for better optimization and integration in to the surrounding.

2 Electric Vehicle Charging Basics

2.1 EV Batteries

EV consist of two batteries, i.e., a high-voltage battery and a low-voltage battery. The high voltage battery, which is considered to be the primary source of energy that supplies electric traction through a three-phase inverter, hence also known as traction battery is usually Lithium-ion based and can be charged through AC-current when on-board charger is active or directly charged via DC-current if off-board charger i.e., DC fast charging is considered. The low-voltage battery is typically a lead battery module which usually based on lead-acid cells. Battery cell consists of an anode (negative pole) and a cathode (positive pole) and an electrolyte. An electrolyte is a conductive liquid/solid element allowing current to flow between the poles, the industry is now focused on carbonates as the electrolyte since it offers great stability, safety and compatibility with the electrode materials.

A typical high-voltage battery is made up of individual cells which combine together to form modules, a type HV battery is shown in the Figure 2.1[49] and in Table 2.1 shows the performance parameter of a typical Li-ion Battery[35].

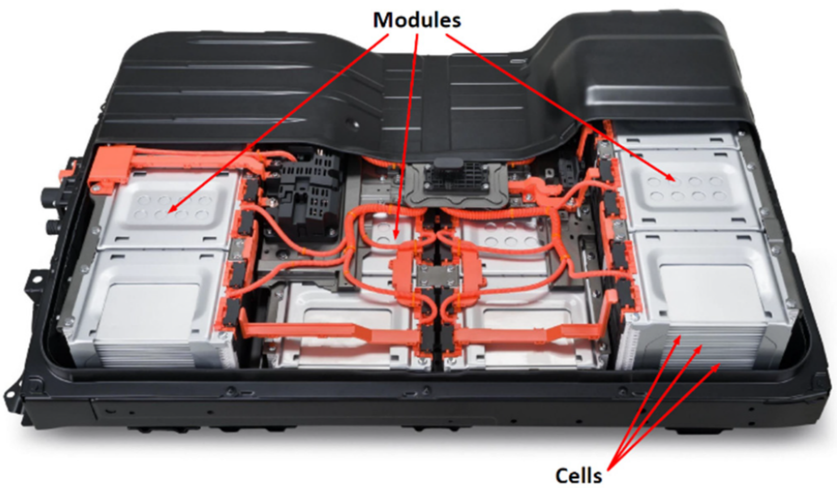


Figure 2.1: HV Battery Pack

Type	Energy Efficiency	Energy Density (Wh/kg)	Power Density (W/kg)	Life Cycles (cycles)	Self-Discharge
Li-ion	70-85	100-200	360	500-2000	Medium

Table 2.1: Performance Parameter of a Li-ion EES

2.2 Battery Terminologies

There are several characteristics parameters that are used to evaluate the performance of a battery in order to use it for the most suitable and reliable application field. In the following, there is an exhaustive list of terminologies:

1. **Cycle Life**: It is the total number of charge/discharge cycles of the battery before it is completely diminished. It is highly affected by the discharging depth, method used for charging, and temperature of the battery.

2. **State Of Health**: It is defined as the ratio of the battery available capacity to the rated capacity and is represented in (%). It is a crucial indicator in order to determine the remaining lifespan and performance of the battery. It is expressed as the following[49]

$$SOH(\%) = \frac{Battery\ Available\ Capacity}{Rated\ Capacity}$$

3. **Internal Resistance**: It refers to the ohmic contribution coming from the components of the battery i.e., collector resistance, electrolyte, conductivity etc. It has high dependence on the SOC of the battery and it is also variable with temperature. It is usually known as equivalent series resistance (ESR) and its value is different depending on if the battery is charging or discharging.

4. **Depth Of Discharge (DOD)**: It is defined as the percentage of battery depleted from a fully charged battery. It is mathematically written as a complement of the SOC[49].

$$DOD(\%) = 100 - SOC(\%)$$

5. **State Of Charge (SOC)**: It is expressed as the battery's current capacity compared to it's total capacity. It is commonly calculated by integrating the battery current in order to estimate the change in the battery capacity over time[49].

$$SOC(t) = SOC(t_0) - \int_{t_0}^{t} \frac{I_b}{3600C_n}\, dt$$

6. **Charge Rate (C-rate)**: It is the rate at which the battery is discharged from the total capacity.

7. **Rated Capacity** C_n: In a single discharge, the number of ampere-hours (*Ah*) provided by the battery. It is determined by several factors: cut-off voltage, discharge current, type and density of the electrolyte, separators, temperature, age,

usage of the battery, no. of electrodes used, design and dimensions. It can also be written as

$$Rated\ Capacity\ (Wh) = Rated\ Capacity\ (Ah)\ .\ Battery\ Rated\ Voltage\ (V)$$

8. **Open-Circuit Voltage (OCV)**: It is measured as the voltage at the terminals of the battery when no current is provided. It depends on the SOC and temperature of the battery.

9. **Rated Voltage**: It refers to the reference voltage of the battery, also known as 'Normal' voltage. It corresponds to the voltage at approx. 50% of the SOC.

2.3 Charging Strategies

Charging of an Energy storage system (ESS) depends on the rate at which the energy is transferred. The performance, life cycle, and protection/safety of a battery is highly affected by the type or the strategy used for charging/discharging the battery. The four basic strategies used are given below without any further detailed view on advanced techniques since it is not within the scope of this paper:

2.3.1 Constant Voltage (CV)

It is a battery charging method in which the battery is charged by providing a constant voltage between the battery voltage while the current reduces through the charging time to zero. One of the drawback of this method is that high value of current is absorbed at the start of the charging process, which could be of course controlled by reducing the constant voltage value. This process could be utilized in all types of charging batteries due to its simplicity[49].

2.3.2 Constant Current (CC)

At a constant C-rate, this method maintain a constant battery current while the voltage increases until it reaches the maximum value, which ends the CC process.

2.3.3 Constant Current - Constant Voltage (CC-CV)

It is a conventional method of charging a Electric Vehicle. At first, the battery is charged at a constant current up to a certain limit i.e., cut-off voltage and then at the second stage, the battery is charged at the constant cut-off voltage, till the battery starts charging at approx. C/10 or less than the defined capacity. The Figure 2.2 depicts the process of typical CC-CV process[62]. The energy transfer is much rapid in the constant current phase than the constant voltage phase, for this reason, it is possible to achieve around 80-85% SOC in a relatively short amount of time.

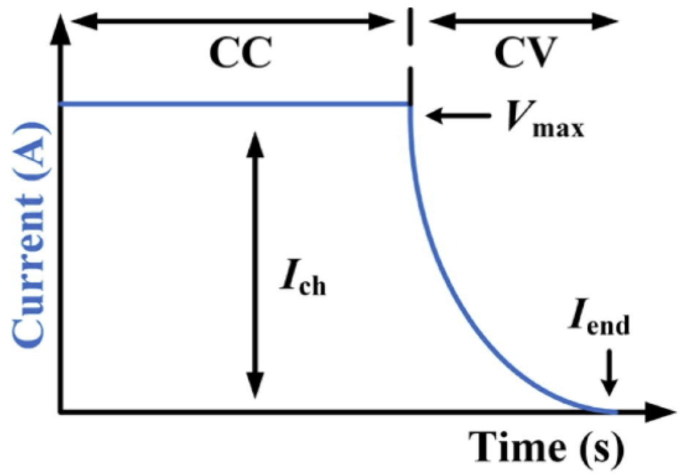


Figure 2.2: CC-CV Battery Charging Profile

2.3.4 Multistage Constant Current - Constant Voltage (MCC-CV)

Knowing the maximum cell voltage along with cell temperature and SOC, the main idea behind MCC-CV is to reduce the charging time, by using a process in which the constant current steps reduces as charging time goes on lowering the charging intensity. When the voltage reaches a pre-determined threshold, the current intensity reduces and a new constant current phase is initialized. In order to fulfil the aim of complete charging, this modified version of CC-CV technique replaces the constant voltage phase. Figure 2.3 represents the MCC-CV process[62].

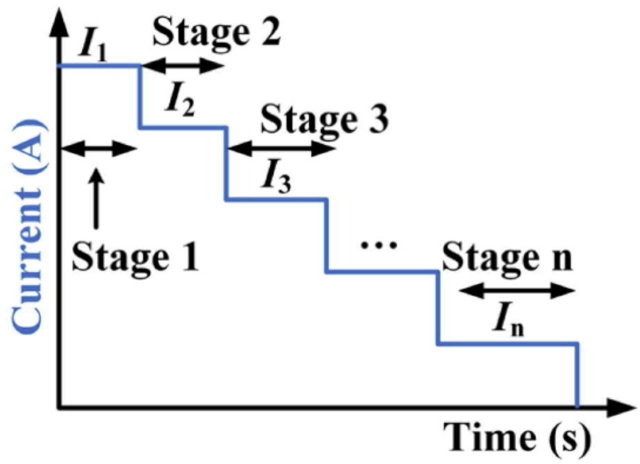


Figure 2.3: MCC-CV Battery Charging Profile

2.4 Electric Vehicle Supply Equipment (EVSE) & Charging Infrastructure

2.4.1 EVSE

EVSE provides the necessary electric power to recharge the battery of an EV. It is commonly known as 'Charging Station' or 'Charging Point'. The following elements are included in the EVSE system.

- Electrical power conductors
- Software
- Communication protocols
- Safety protocols

The above mentioned components will further be discussed in detail in upcoming sections. One of the important element of an EVSE is a charging pool which contains several charging stations/points, each of them consist of several connectors and each charging point is limited to one connector activation at a time[35]. For better understanding and clarification, the EVSE Structure is explained in figure 2.4[35].

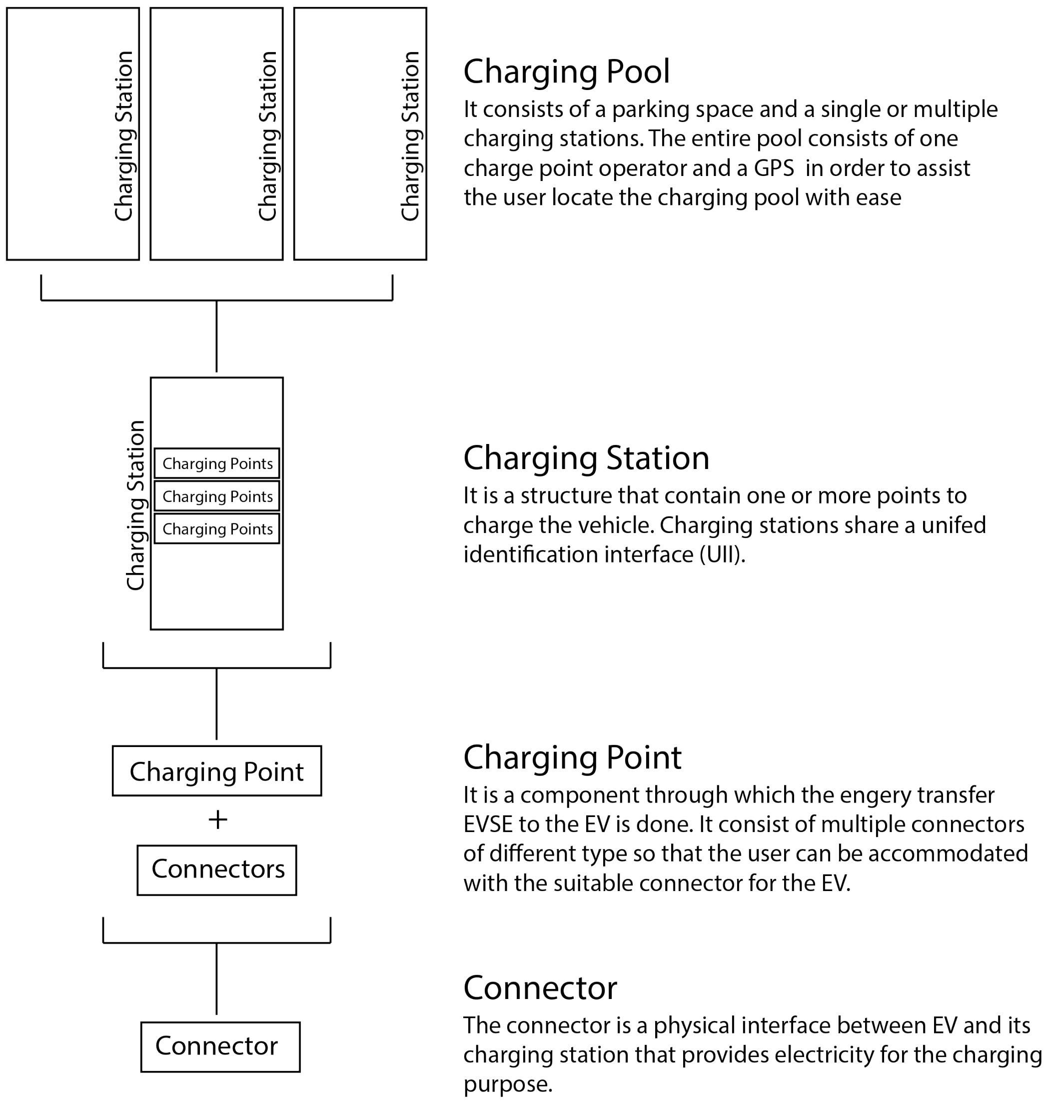


Figure 2.4: EVSE Structure

2.4.2 Charging Infrastructure

The charging infrastructure of an EV consists of the following components :

- Power structure
- Control structure
- Communication structure

And also shown by the Figure 2.5 [11]

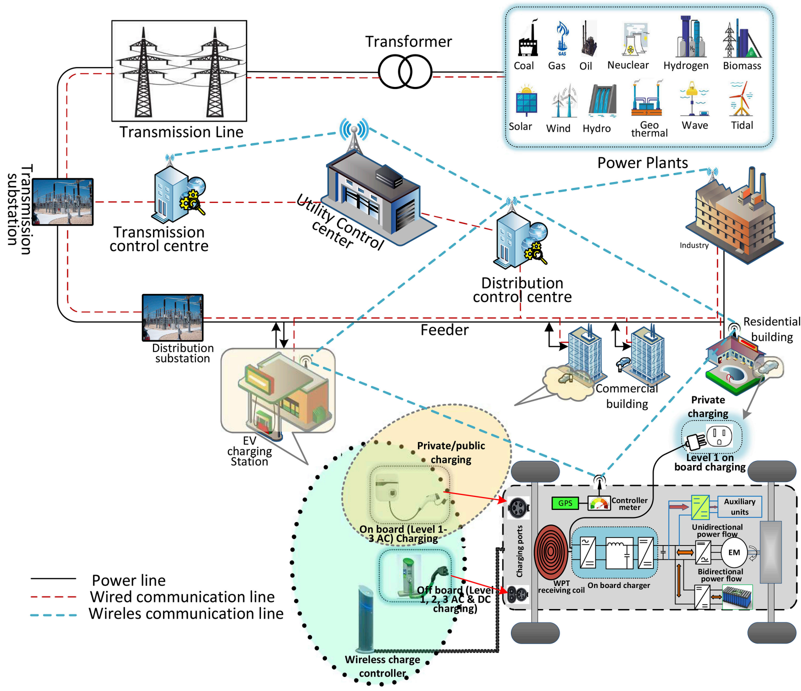


Figure 2.5: Schematics of an EV charging infrastructure

Power structure

This structure consisting of electric circuits provides power flow between the EVs and the grid [47, 11]. It is further classified depending on the type of power used (AC/DC), charging circuit (on-board/off-board), charging contact requirements (conductive/inductive), and direction of the power flow (uni-directional/bi-directional).

Control and communication structure

These two aspects are crucial for real-time monitoring and control of an EV-charging system [14]. Considering that the EV charging put additional load demand in the power system, it can be optimized by proper communication and signalling of an EV with the charging station connected with a grid in order to reduce peak demand and load.

- **Control architecture in EV charging**: EV charging control structure comprises of distribution grid, EV charging stations and EVs itself and further they are classified according to the control structure, coordination, and mobility [11].
- **Communication network for EV charging**: In order to optimize the EV charging management, a proper communication is needed between the EVs, EVSEs and the grid [41, 20] as depicted in Figure 2.6[11]. Today, protocols are wired and wireless based communication network technologies, and these protocols are applied in different networks such as, home area network (HAN), industrial area network (IAN), building area network (BAN), neighborhood area network (NAN) and field area network (FAN). The main functions of these network are to monitor and control the charging and discharging of an EV [11].

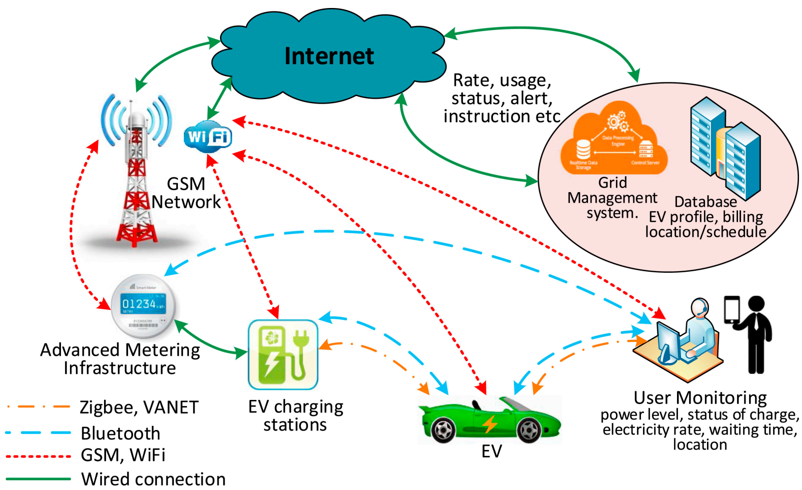


Figure 2.6: Charging infrastructure communication network

Finally, following challenges have to be considered when setting up the EVSE and charging infrastructure.

- Standardization and regulation
- Charging time

- Policies regarding demand/distribution

In order to cut back cost on EV batteries and minimize the requirements, enough availability of the charging infrastructure is required especially in dense areas. The specific set of requirements and specifications varies from country to country, which directly depends on the voltage supplied, frequency. standards. and grid connection[5].

2.5 Charging System and Classification

A typical EV charging system consists of a charging point, a charging coupler, an on-board charger, and a battery pack[49]. Further, a control system which is equipped with a set of standards in alliance with the regions/countries in order to have a transparent and smooth communication and transfer of energy between different components of the system is highly crucial. The HV battery [2.1] is the primary source of traction that must be regularly charged, thus an EV charging system ensures the proper charging process. It is based on the principle power conversion stages, which is the gate way between the grid and EV batteries for electrical energy transfer[49]. Figure 2.7 indicate the classification of charging methods utilized for the EV charging.

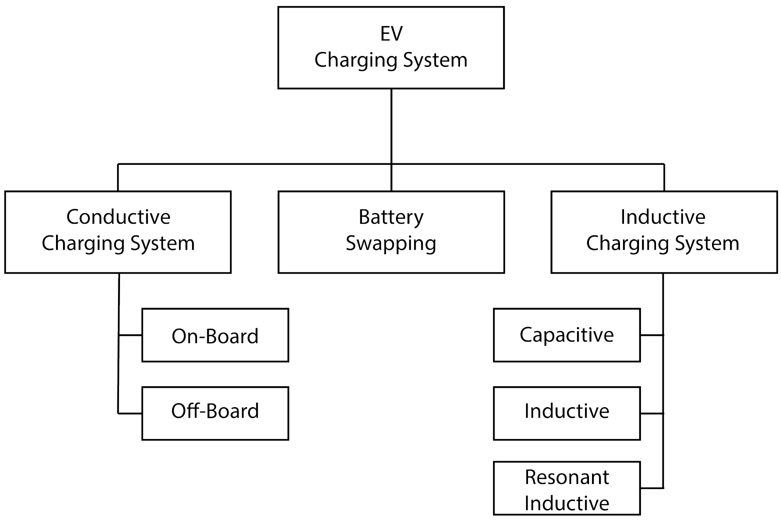


Figure 2.7: Charging System Classification

2.5.1 Conductive Charging

In this type of charging system, direct contact between the connector and the charging inlet is made in order to transfer power. The biggest advantage of such system is the efficient power conversion and robustness. The components comprising of conductive system are AC-DC power factor correction (PFC) converter, which is then followed by the DC-DC converter and is connected between the power electronics interface (PEI) and the power supply for charging by a hard-wired connection[36].

They are classified [2.7] as on-board and off-board charging systems. On-board charging system is well integrated within the EV, and since there are certain limits w.r.t, weight, cost, space and size of the EV, the power transfer is limited. While, off-board chargers have no specific constraints because the components of the charger are not specifically integrated into the vehicle but are installed in the public parking lots i.e., malls. universities and hospitals[35]. On-board chargers are used generally for slow charging while off-board charging are intended for fast charging and lower charging time due to no specific constraints. Figure 2.8 shows the structure of an on-board and off-board charging infrastructure [55].

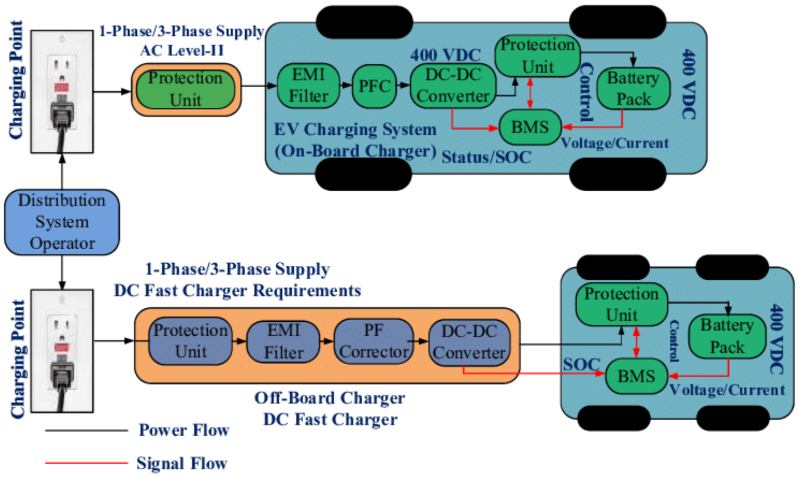


Figure 2.8: On-board and Off-board conductive charging infrastructure [55]

2.5.2 Battery Swapping

This technique allows the EV users to exchange/replace their drained battery with a fully charged one. This type would possibly maximize the user acceptance and minimize the charging time needed by the EV batteries. Also, with this, there would be reduced load demand surge, resulting in increased cost savings. Considering the drawbacks, the EV batteries are not standardized, obstructing the way of these stations into one specific type [5].

2.5.3 Inductive Charging

Inductive charging, also known as wireless charging working principle is based on mutual induction to transfer power from the grid to the EV i.e., Inductive power transfer (IPT). One of the advantage is that it does not require any physical connection between the grid and the EV. However, when compared with the conductive charging, they are relatively less efficient especially when there is a misalignment between the wireless coils. They are usually classified as inductive, capacitive and resonant inductive. Even though, they pose to be user friendly due to contactless charging, they are highly complex and have low power density[5]. Roadbed inductive charging which is still under research has the ability to recharge the vehicle while it is in motion, this approach is usually suggested for vehicles on highway in order to reduce range anxiety [35]. Figure 2.9 shows the schematic of a typical wireless charging system for an EV [56].

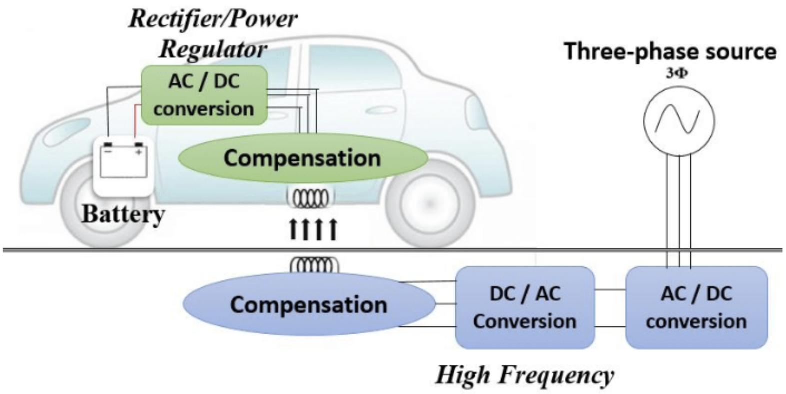


Figure 2.9: Principle diagram of a wireless charging system[56]

3 Electric Vehicle Charger Classification

The current and future progress of EVs are dependent on the battery chargers, the parameters related to battery chargers are the charging duration and the battery life. For an optimal charger, it needs to be highly reliable, efficient, compact, not so expensive and should have high power density [64, 5]. Another important perspective is that the charger with minimal distortion draw utility current and also with high power factor, maximize the real power availability from the utility outlet. It should be able to minimize harmonics and DC injection following standards available depending on different location/country such as, (IEEE, SAE, NEC).

Charging of EV can be performed either by single-phase or three-phase chargers, with uni-directional or bi-directional power flow abilities depending on the components of the EV charging system [35]. EV chargers are further classified as conductive and inductive chargers as discussed in 2.5. Conductive charging are well developed, while research and development are still being done on the inductive charging technology.

3.1 Classification of EV Chargers

The Electric vehicle chargers can be classified according to the several criteria, some of them are stated below [49]:

- Charger location
- Direction of energy transfer
- Charger structure
- Type of connector
- Power conversion stages

Considering the above scheme, a brief classification types with their advantages/drawbacks are described below [49, 5, 35]:

3.1.1 On-Board Charger

Most of the components needed for the charging process are installed in to the EV, and since it is integrated on to the vehicle, the charging power is limited due to size, weight, space and cost of the EV. Figure 2.8 illustrates the components of an on-board charger. Some of the advantages/challenges are listed below:

- Low energy transfer rate
- Battery heating issue not so important
- Increased weight of the EV
- Longer charging time
- Low-level power transmitted
- On-board rectifier controls the Battery management system (BMS)
- Size and weight of an EV limited
- Recharge possible at any electrical outlet with low level communication and safety protocols
- The maximum current capacity, charging station phase configuration and the supply voltage are the components needed by the on-board BMS.

3.1.2 Off-Board Charger

All the components required for the EV-charging and discharging process are inside the EV charging station. Figure 2.8 shows the structure of an off-board charger. The overall cost is really high when compared with the on-board charging due to recurring power electronics, and no limitations on size and weight since most of the charger components are outside the vehicle, in the charging station. Some of the advantages/challenges are listed below:

- High energy transfer rate
- Battery heating issue crucial and must be solved
- Lower EV weight when compared with on-board charger EV
- Better BMS
- Recharge at any electrical outlet not possible

- Shorter charging time
- Much higher costs as compared to on-board
- BMS integrated in to the charging station raising the overall cost
- High maintenance cost
- Since the BMS not on-board, identification of defects in battery bank cells not possible

3.1.3 Uni-Directional Charger

The transfer of energy, as the name suggests is only one way i.e., from the charging station to the EV battery, also known as Grid to vehicle (G2V). Considering the components of a uni-directional charger, it generally have a diode bridge rectifier (DBR) with a filter and DC/DC converters, usually it is a single stage converter in order to have limited size, weight, cost and losses. It utilizes high-frequency isolation transformers for better isolation during the charging process. Simple and straight forward charging technique makes it an easy option for grid to manage EV charging process.

3.1.4 Bi-Directional Charger

As the name suggests, the energy transfer can be both ways i.e., from the grid to the EV battery (G2V) or from the EV to the grid (V2G). When compared with uni-directional charger, it has two power stages, an active grid connected AC/DC bi-directional converter that validates power factor (PF) to be unity, while the second one is a DC/DC bi-directional converter with the main aim of controlling the charging current [18]. Also, these charger uses both isolated and non-isolated configuration of the circuits.

The schematic of a uni and bi directional charger is given in the Figure 3.1 [21, 69].

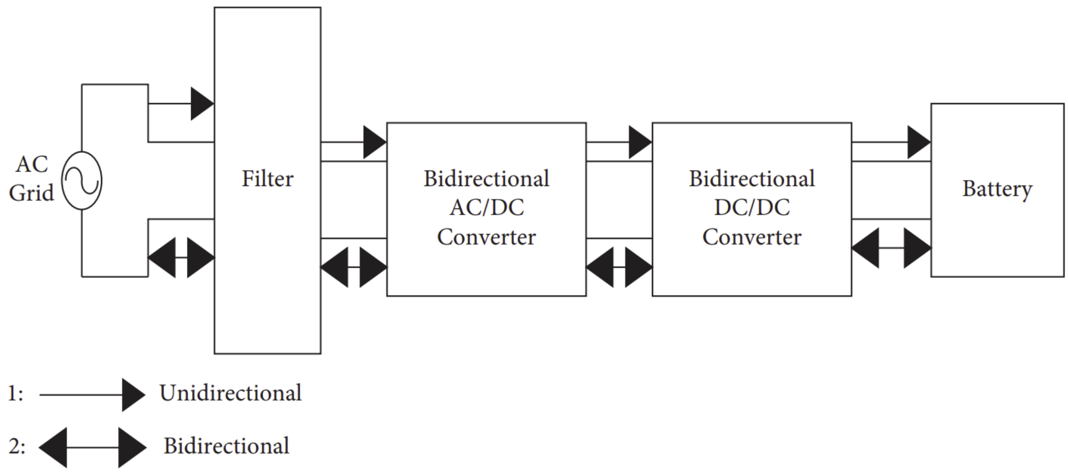


Figure 3.1: Uni and Bi directional charger scheme

3.2 Charger Topology

Here, the main focus would be conductive on-board and off-board charging technology. The main component of a charger is considered to be AC/DC Converter at the front-end. Adaptation of various techniques has been done in order to correct the power factor (PF) [35]. Without getting into depth since it is not in the scope of the thesis, brief analysis is presented in this section.

The single-phase active power factor (PF) correction technique has two types, namely single-stage and dual-stage approach. For low power demand, single-stage approach is recommended and it has low-frequency ripple in the current at the output. Considering the safety, isolation is difficult, where dual-stage approach comes in, that has galvanic isolation. Focusing on conductive chargers, which has a physical connection between the grid and the EV consist of the following components: PF corrector, AC/DC rectifier, DC/DC Converter.

The on-board chargers residing on the EV contains two power conversion stages:

1. **AC/DC Converter**: The main function is to rectify the single/three phase supply from the utility.

2. **DC/DC Converter**: It is utilized to control the current flow for charging.

The off-board charger utilizing components outside the vehicle usually consists of fast and high energy transfer chargers. The topologies used for on-board/off-board chargers are largely set on the structure the AC/DC and DC/DC converters posses. In

Table 3.1 [35] & Table 3.2[35], there is a summarized comparison of different front-end AC/DC converters technologies and DC/DC converters

Converter Configuration	Switches		THD (%)	PF Range
	Active	**Passive**		
Three-phase PWM converter	6	0	Low	Wide
NPC Converter	12	6	1	Wide
Vienna Converter	6	6	1	Limited
Three-phase buck converter	6	6	Low	Limited

Table 3.1: Comparison of front-end AC/DC Converters

Converter	Switches		Advantages	Disadvantages
	Active	**Passive**		
Boost converter	2	0	Simple to control	Limited voltage and current capability
Interleaved boost converter	6	0	Simple to control high voltage and current capabiltiy	Limited voltage capability
Three-level boost converter	4	0	Small current ripples	Modularity not possible
Flying capacitor converter	4	0	Modular with stable operation	Low protection
Phase shifted full-bridge	4	4	Simple to control	Low efficiency
LLC converter	4	4	High PF	Low efficiency
Dual active bridge converter	8	0	Output voltage wide range	Low efficiency
CLLC converter	8	0	High PF	Control complexity

Table 3.2: Comparison of DC/DC Converters

3.3 EV Chargers Influence on the Power Network

Due to increase in EV demand, EV chargers and charging stations are on the rise, which not only comes with benefits but also with adverse effects, out of which its impact on the utility grid is considered here in this section.

Why consider EV impact on the utility grid? One of the crucial requirement of a charging station is that it must be supplied with a load consisting of continuous power at a desired time of EV charging independent of location, which on the contrary is unfavorable to the power network companies, since the electricity provided is usually of a homogeneous profile otherwise there is harmful impact on the grid in long run, such as, electrical failure. This part exploits different impacts of the charging station on the grid depending on the energy related and the power related quality issues [54, 35].

3.3.1 Effect on Grid's Energy

The biggest concern considering EV charging especially Fast charging is the increment in the load demand in a certain period of day especially which disturbs the flattened load curve profile on the feeders.

A study was done considering the base-load, base-load with Plug-in, base-load with EV and base-load with EV and Plug-in as depicted in Figure 3.2 [42]. The goal of such figure is to obtain more or less a flattened curve, but as the diagram suggests adding EV and Plug-in moves the curve to the highest amount. With red and green curve, the consumption is lowered in the afternoon because the radiation is the highest [54]. While when Plug-in is combined with the EV, the peak decreases.

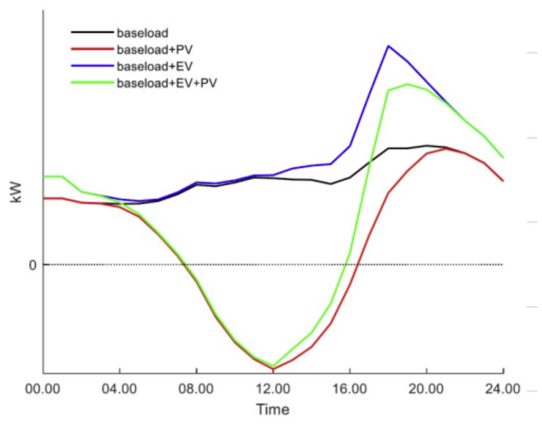


Figure 3.2: Residential distribution grid effected by the EV analysis

Also the study in [46, 52] suggests that the effects of charging in two different scenarios that are, uncontrolled and indirect controlled on a low voltage network used as in the case study is detrimental especially of the uncontrolled charging on the grid is much more significant than the indirect one. In the end, it was concluded that EV sharing the indirect controlled charging could be advantageous in the network.

3.3.2 Effect on Power Quality of the Grid

EV dynamic characteristics have an effect on the grid power, such as harmonics, swell, voltage and phase imbalance. EV manufacturers do take this fact in to consideration when manufacturing vehicles especially the grid power quality standard in order not to impact the grid devastatingly. In the load current, harmful sequence components produced in the EV charging stations, also impact the converter's performance, since they produce second-order harmonic ripple in the DC link voltage, resulting in grid's current distortion[54].

3.3.3 Solutions to Minimize Grid Impact

In literature, various researches on this topic have been done in order to reduce risk of having negative impact on the grid. If the strategy to charge the EV is well-planned and well coordinated then the overload issue on the grid can be minimized. The losses especially can be reduced by optimization of smart gird metering system to balance the supply and demand. In order to lower the current harmonics when line current is drawn by the EV charger, the procedure is to install an input line filter for conditioning of the power on to the EV charger, also adopting advanced PWM strategies for effective lower order harmonics reduction, and to reduce the electromagnetic interference (EMI), common mode current should be avoided. Finally, using RES would beneficially reduce negative implication of the EV charger on to the grid.

4 EV Charging Standards

Code: A set of rules and regulations proposed to be followed, it is not entirely a law, but can be adopted into the law. As an example, according to the National Electric Code (NEC) 625, EVs must follow strict charging guidelines for safety purposes [6].

Standard: It is the procedure to meet the set of codes. The set of standards are used by the product designers, development sector, installation sector and the operation sector. As an example, Society of Automotive Engineers (SAE) J1772 contain procedures aligned with specific set of codes for the production and installation of EV couplers [6].

The purpose of the EV standards is to create a strong foundation for broad market penetration and to meet customers expectations, and with that since the past two decades the EV charging integration and market has increased. On the contrary, it has brought in new challenges and requirements in to the domain of automotive industry, electric network and policy making. EV standards ensure proper functioning, safety, interoperability, and integration [2].

Considering charging and grid integration standardization, Society of Automotive Engineers (SAE) and the Institute of Electrical and Electronics Engineers (IEEE) are the two main contributors. While for EV Conductive charging systems, the SAE and International Electrotechnical Commission (IEC) standards are widely adopted. Some of the widely adopted standards for All EVs and PEVs are listed in Table 4.1 [2], further discussions especially related to the ones significant for this paper will be made in the upcoming sections.

Standard	Description
SAE J1772	Conductive Charging of AEVs and HEVs
SAE J2344	EV Safety
SAE J2894/2	Power quality requirements
SAE J2953	Interoperability of EV and charger
SAE J2847/1	EV and grid communication
SAE J3068	EV power transfer using 3-phase capable coupling
IEC 60038	Standards for the voltage for charging applications
IEC 62196	Standards for the EV conductive charging components
IEC 60664-1	Installation coordination for charging equipment in low-voltage supply
IEC 62752	Standards for cable control and protection devices
IEC 61851	Safety specifications of charging stations

Table 4.1: EV Charging Standards

4.1 Types of Standardization

4.1.1 Charging components

This category consists of EV conductive charging components such as, connectors, plugs, outlet-socket, and inlets provided by IEC 62196/61851 and SAE J1772.

4.1.2 Grid integration

EV charging and discharging through grid is managed by the grid integration codes and regulations, which further includes power regulation standards, safety, and power quality requirements, standardized by IEEE 1547, Underwriters Laboratories (UL) 1741.

4.1.3 Safety

Protection standardization is crucial for the EV charging cycle and grid integration. The organizations mainly involved in this sector are NEC and NFPA with main orientation towards security and safety.

NFPA Standards

They are usually associated to the public safety for fire, electricity, and life. In terms of EVs, they are usually concerned with the customer side especially for cables and electrical equipment safety and precautions [33].

NEC Standards

It deals with EV industry safety measures specifically in the EV charging equipment specifications, it consists of two sections NEC 625 and 626. NEC 625 deals with EV charging systems off-board, which includes, equipment connected to feeder and networks for EV charging, also plugs, wires, installation procedures of charging station equipment for EVs. NEC 626 specifies standards for electrical equipment and conductors after the vehicle used for trucks packing, it includes safety systems, suspensions, cables and back feed protection [33].

For better understanding Figure 4.1 [51] shows a depiction in which area, which organizational standards are imposed.

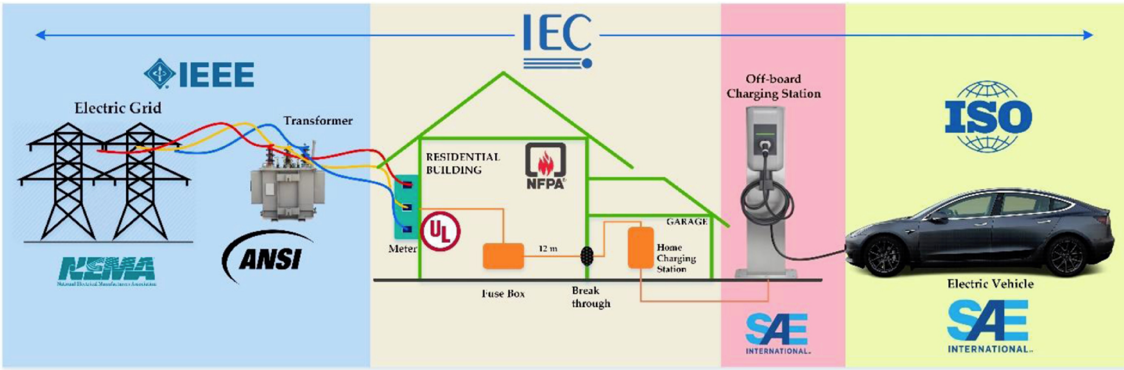


Figure 4.1: EV charging international standards

4.2 International Standards

Among various international standards, the main focus will be on IEC and SAE standards which have been comprehensively developed for EV charging stations. In this section, IEC and SAE standards are discussed in detail.

4.2.1 IEC Standards

Description

IEC is a British standardization organization, developing standards for electrical and electronics. It has established various international standards especially for EV charging, the illustration in Figure 4.2 [51] shows various standards that specifically deals with specific sections of the EV charging sectors. And in order to be more precise, the Table 4.2 [51] shows a list of IEC standards specifically of this paper concern and their description.

Standard	Description
IEC 61851-1	Part 1: General requirements
IEC 61851-21	Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply
IEC 61851-22	Part 22: AC electric vehicle charging station
IEC 61851-23	Part 23: DC electric vehicle charging station
IEC 61851-24	Part 24: Digital communication between a D.C EV charging station and an EV for control of D.C charging
IEC 62196	Plugs, socket-outlets, connectors, and vehicle inlets

Table 4.2: IEC Charging Standards

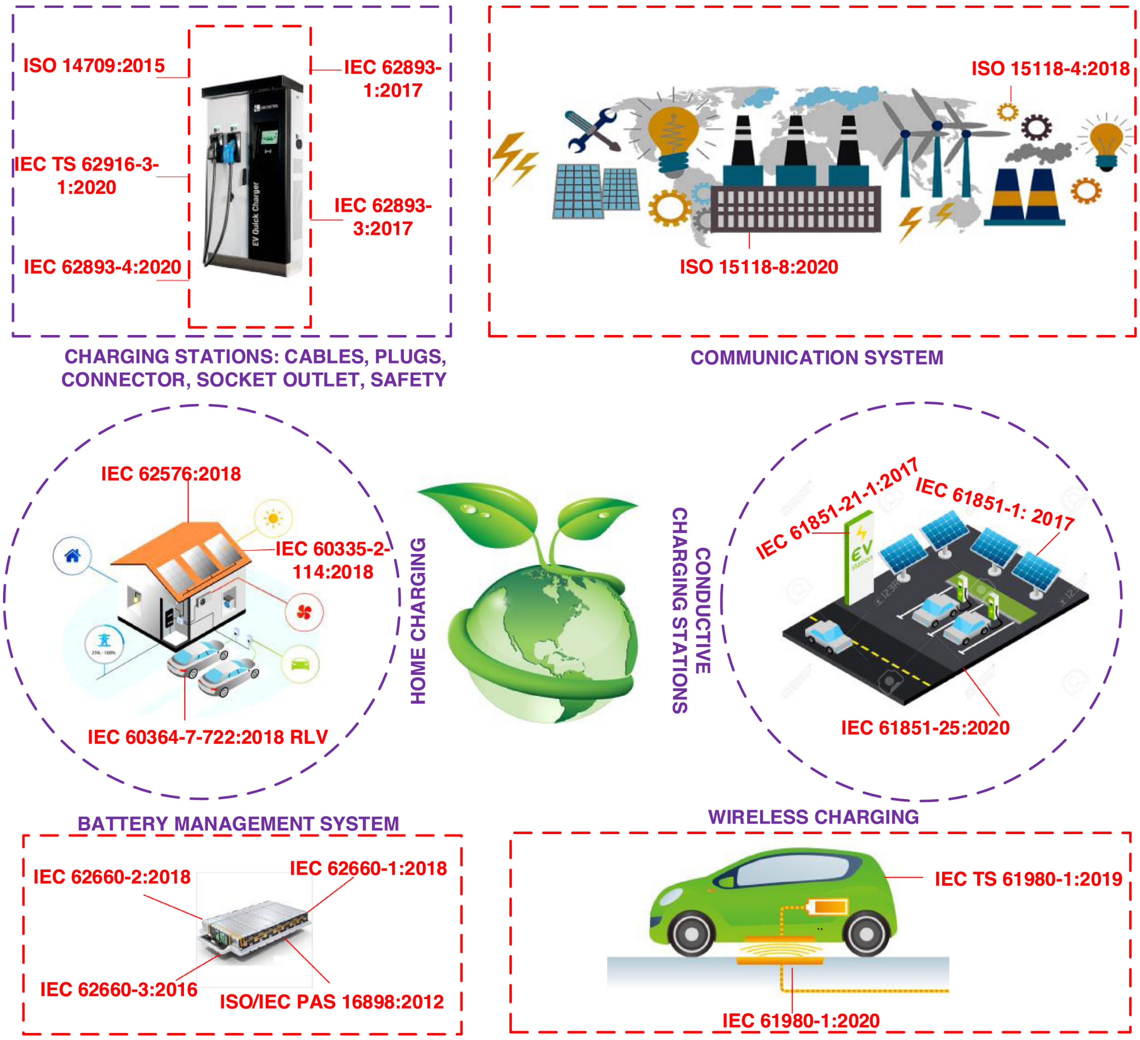


Figure 4.2: Various IEC standards dealing with EV charging

In present, the standard utilized at European level is IEC 61851 dealing with conductive charging station which also includes characteristics and operating conditions of EVSE, connection between EV and EVSE and electrical safety for EVSE [17, 51]. Another important standard is IEC 62196 which covers requirements and specifications regarding cables, plugs, socket outlets, vehicle connectors, vehicle inlets, and thermal management of the cables for EV charging [51].

Charging Modes

The standard first describes first classification of the charger type as a function of its rated power along with the time it requires to fully recharged, the Table 4.3 [17]. IEC 61851-1 then defined 4 modes of the charging, which are based on the following points:

- The EV receiving power type (AC single-phase, AC three-phase, DC).
- The voltage level (AC single-phase voltage **110V**, AC three-phase voltage **480V**).
- The possibility of uni-direction or bi-direction communication between EVSE and EV with the presence or absence of grounding and control lines.
- Device protection presence and location.

Type of power	Rated power (kW)	Usage
Normal power/slow charging	< 3.7 kW	Domestic application
Medium power/quick charging	3.7 - 22 kW	Private and public EV
High power/fast charging	>22 kW	Public EV

Table 4.3: IEC 61851-1 classification as a function of rated power

Finally, the 4 modes are presented in the Table 4.4 [24, 2] Section 6.2.

Connection Type	Current rating (A)	Voltage level (V) @ supply side
AC Supply	< 16 A	< 250 V a.c. (single-phase) / < 480 V a.c. (three-phase)
AC Supply	< 32 A	< 250 V a.c. (single-phase) / < 480 V a.c. (three-phase)
AC Supply	32 A - 250 A	< 250 V a.c. (single-phase) / < 480 V a.c. (three-phase)
DC Supply	250 A - 400 A	600 V - 1000 V

Table 4.4: 4 Charging Modes [24, 2]

1. **Mode 1:** According to the standard [24] Section 6.2, mode 1 utilizes the power and protective earth conductors. It consists of circuit breaker and earthing system for safety against leakage and overloading conditions [2]. Depending on the location, the current ranges between 8 A to 16 A while the AC grid voltage level

is either 240 V in single-phase and 480 V in three-phase and EV charging done via regular socket. In some countries according to the standards specifications, mode 1 charging is prohibited by national codes: US because in this mode, there is no communication between the vehicle and the supply and also it is considered to be a potential unsafe charging process.

2. **Mode 2:** The major difference mode 2 brings is that, its cable is merged with protective device known as In-cable control and protection device (IC-CPD) which ensures proper control and protection, hence it offers medium safety level[2]. It offers slow charging preferably installed at residential locations. The cable used provides safety against protective earth detection, overheating protection and over-current protection. The basic logic is to connect the EV to the socket by means of this cable, which is also called in-cable control box (ICCB). This cable then make sure of the insulation and proper operation of the cable and the EV, but its not able to have the same level of control between itself and the grid. As it is stated in the [24], it utilizes power and protective earth conductors along with control pilot function and protection against shock being a part of the EV and the plug or in-cable control box. One of the possible solution offered by the car makers were to introduce a thermistor on the Schuko plug for thermal management, if the temperature is to high, it opens the connection between the cable and the grid. This method is widely adapted by the EV users.

3. **Mode 3:** In this mode, EV is connected to AC supply network via dedicated EVSE where the control pilot function introduced in mode 2 extends here to the control equipment of the EVSE i.e., connected permanently to the AC main supply (grid) [24]. For protection, control and communication, the EVSE is permanently installed (usually on the wall also known as wall-box). The wall-box ensures in accordance with standards proper safety levels close to that of the public charging stations. In mode 3, there is possibility of higher power rating usually reaching up to 60 kW to 120 kW [2] which is due to the fixed EVSE. As indicated in mode 2 charging, the cable consists of the earth and control pilot. This mode is a better and reliable way to charge the vehicle but requires expensive equipment when compared with the modes above.

4. **Mode 4:** This mode uses DC power connection type in order to charge the EV, which is done by off-board charging with dedicated EVSE to deliver DC current to the vehicle directly since the power conversion from AC to DC is completely performed by the off-board charger, usual usage is in the public stations, since it requires high amount of investments due to expensive off-board components. The EVSE consists of all the features, such as control, communication, protection features and the control pilot feature extends further to the EVSE permanently

connected to the utility grid [2, 24]. The maximum current allowed by this mode is 400 A with the power rating greater than 150 kW [2]. One of the advantage of this type, the power electronics circuit with in the DC charger adjusts the output voltage in order to control the DC charging current [34]. Even if the charger can provide a couple of hundred kW (Ultra fast charging), still the power supplied to the EV is limited since the battery charging efficiency tremendously reduces as the power increases, hence battery management system limits the maximum charging power to take in to consideration the temperature limit of the battery system on the EV, so currently the limit of the continous power is between 40 kW to 130 kW [34].

For further clarification, the illustration in Figure 4.3 [34], gives a general idea on the working of the 4 modes.

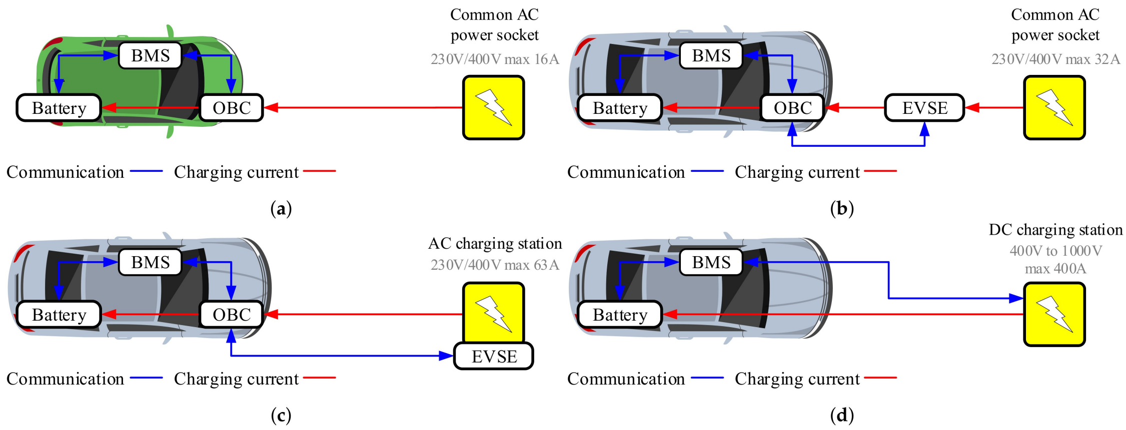


Figure 4.3: Working of the 4 Modes.

Charging Couplers

Considering IEC standards, they defined two different types of socket-outlets that are currently being utilized with in the European market:

- **IEC type 2 Coupler:** This coupler first proposed in 2009 by the German company ’ Mennekes’. The IEC committee defined the charger ’Type 2’ in the standard IEC 62196-2, which can be utilized as both single and three phase AC coupler, specifically and popularly known as ’Mennekes’ charger as well. The EU commission in January 2013, decided that all EVs in the Europe must have this standardized connector installed in order to resolve the issue of lack of interoperability [17].

According to the standard IEC 62196-2, 'Type 2' coupler was designed for single-phase AC charging up to 7.4 kW (230 V/32 A) or 43 kW from a three-phase AC power supply [49]. Figure 4.4 presents better the configuration in which 'Type 2' can be utilized, while according to EU standards, only the first configuration is being used [65]. While the Figure 4.5 indicates the Type 2 coupler and the devices associated with it [12]. The Table 4.5 in accordance to the IEC 62196-2 states the main specifications of the coupler.

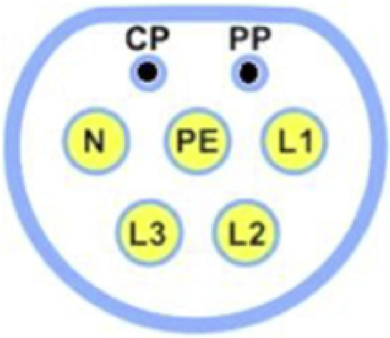
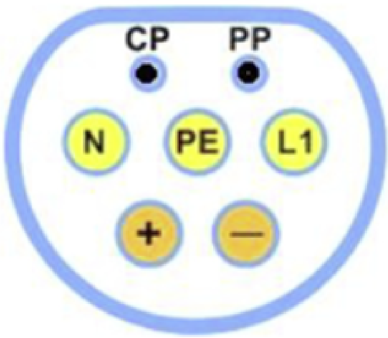
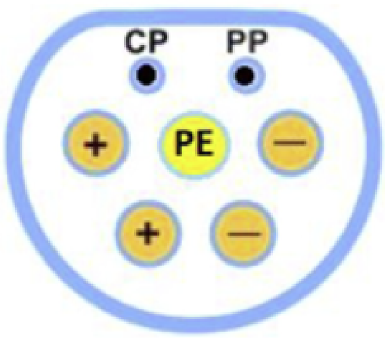
Configuration	Supply Type Max.	Voltage @ Max. Current
	Single-phase AC Three-phase AC	500 V @ 1 × 70 A 500 V @ 3 × 63 A
	DC-Low	500 V @ 70 A
	DC-Mid	500 V @ 2 × 70 A

Figure 4.4: AC and DC possibilities with Type 2 EV inlet.

Modes	Mode 1	Mode 2
Maximum Capacity	4 kW	22 kW
Input Voltage	250 V Single-Phase	480 V Three-Phase
Current Rating	16 A	32 A
Standard used	IEC 62196-2 / 61851-22/23	IEC 62196-2 / 61851-22/23

Table 4.5: Specifications of Type 2 Coupler

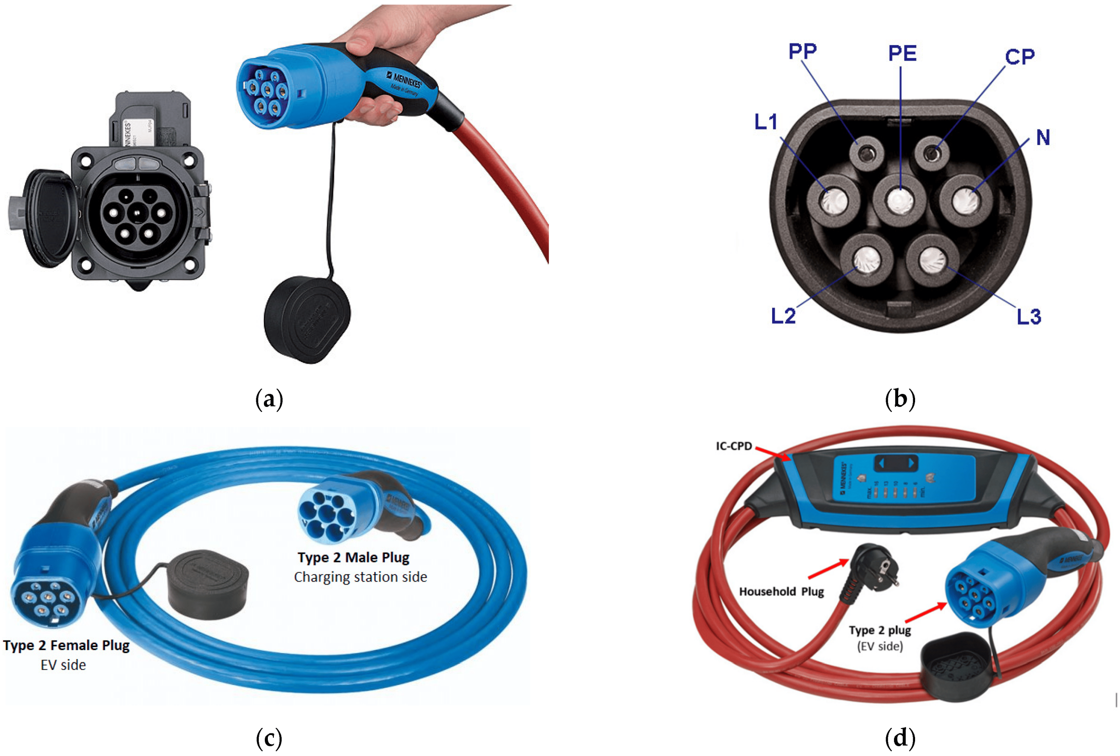


Figure 4.5: Type 2 coupler and other components: **(a)** Type 2 coupler i.e., Inlet (left) and Plug (right), **(b)** Pin layout of the plug, **(c)** Type 2 to Type 2 charging cable, **(d)** Type 2 with portable EVSE made by Mennekes.

- **CCS Combo 2:** CharIN e.V also known as Charging Interface Initiative e.V. a registered association put together by a number of companies namely, Audi, Daimler, Mennekes, Opel, Phoenix Contact, Porsche, TÜV SÜD and Volkswagen was the main organization that gave rise to the Combo connector. One of the key benefits of Combined Charging System (CCS) is that it utilizes a single connector for both AC and DC charging by making use of separate pins. The charging and connector are in accordance with the IEC 62196-1, IEC 62196-2 and IEC 62196-3 standards. Considering the AC charging process, the signalling and communication for charging complies with the IEC 61851-1, 61851-22, and for DC charging process, its IEC 61851-1, 61851-23, ISO/IEC 15118, DIN SPEC 70121 and the SAE J2847/2. Also, when considering the signalling and communication, the control pilot has both low and high level communication i.e., PWM and power line communication (PLC) respectively [30].

Figure 4.6: Pin Layout of CCS Combo 2, Vehicle connector (*left*), Vehicle inlet (*right*)

The figure 4.6 [30] indicates the connector on the left and the vehicle inlet on right which are derivative of the AC Type 2 connector. In addition to the two signal pins namely control pilot and proximity pilot, and protective earth pin, the DC plus and minus pins are utilized for the DC Fast charging process. While for the vehicle inlet, the pin configuration is same as the AC Type 2, only with the addition of DC plus and minus pins.

According to ITT Cannon, makers of CCS 1 and CCS 2 DC fast charging connectors, the maximum charging power achievable with CCS-Combo 2 is 200 kW, with rated current from 60 A - 200 A and up to 1000 V [8]. The maximum values do not provide the actual scenario of charging of a BEV since it also depends on the vehicle components temperature range, voltages and power requirements limiting the actual Charging current, voltage hence overall power supplied. For further clarification, the following table 4.6 [2] provides necessary data of a DC Fast Charging connector i.e., CCS-Combo 2.

Modes	Mode 4
Maximum Capacity	350 kW
Input Voltage	200-1000 V
Current Rating	500 A
Standard used	IEC 61851-23/24, IEC 62196-3/DIN EN 62196-3

Table 4.6: CCS-Combo 2 Specifications

Safety Aspect

- **Type 2 Connector:** According to the IEC 62196-1, 10.1 [28, 10], the designing of the accessories i.e., the live parts of socket-outlets and vehicle connectors, when wired for normal usage, and plugs and vehicle inlets live parts, when connected partially or completely engaged with the complementary accessories, are not accessible. Which can be tested by test finger, nevertheless the designing of the plugs regulated by the standards are done in such a why that access to the live parts with test finger is not so possible, hence further testing are not so required because of this reason.

  Considering the connection of the connector with the vehicle inlet, the following process showed in Figure 4.7 is considered that is in accordance with the safety standards indicated in IEC 62196, 6.8 and 10.3 section [28]. Considering the Insertion of the plug, the first step indicates that the longest pin i.e., Protective Earth pin establishes the connection first. After that is the Neutral pin connection, that can be made/braked simultaneously, further in step three, the connection of the L1, L2 and L3 (Live line to provide current either in single phase or three phase) is established, that again can be made/braked simultaneously and then finally the connection of the control pilot (CP) and proximity (PP) is made used for communication, controlling and signalling purposes, the proximity connection can also be made before the control connection. After these four steps completion, is the starting of the actual charging process. Then considering the withdrawing process, CP and PP pins are the first to be disconnected, while proximity connection can be braked before the control connection also. Then the L1, L2, L3 are disconnected that again can made/brake simultaneously, followed by the neutral pin detachment and finally the earth contact pin being the longest pin disconnected in the last [10]. Hence for safety reasons, the earthing connection is made first while the pilot connection is made last, also during disconnection, the pilot disconnects firsts while the earth connection breaks the last [24].

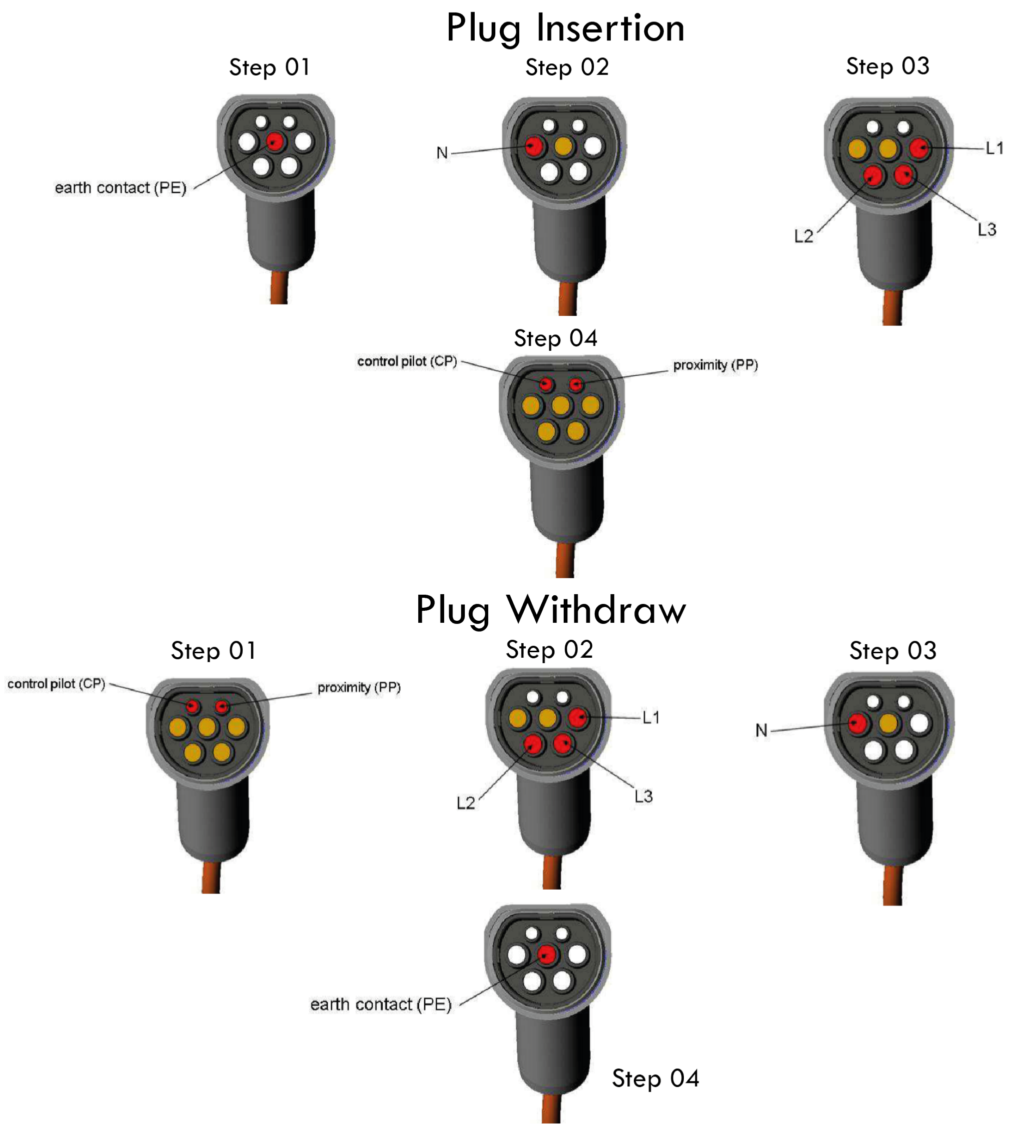


Figure 4.7: Type 2 Connecting Sequence according to the IEC 62196-1, 6.8 and 10.3

The AC EV charging station connected to the EV made in normal conditions of usage, such that the equipment used reduces the risk of fire, electric shock or injury to the person [23] achieved by the general requirements in IEC 61851-22 standard and compliance assurance is done by significant tests according to the standard. Further electrical safety according to the IEC 61851-22 is given below.

- **Protection against indirect contact:** Additional protection against electric shock as of IEC 61851-1 7.4.1 should not be reset automatically, but there should be an availability of a manual reset to the user. While as of IEC 61851-1 7.4.2, the automatic reset of protection devices must comply with the national regulations.

- **Earthing electrode and continuity:** In order to conduct potential fault currents to the earthed point of the AC supply network (mains), all exposed conductive parts of the AC electric vehicle charging station that could be connected to the supply voltage source under fault conditions must be connected together in a way that allows them to conduct electricity properly [23],9.2. While the checking of the compliance s done by testing the electrical continuity between exposed conductive parts and earth circuit. Any exposed conductive portion and the charging station's earthing connection are connected by a current of 16 A, which is drawn from a d.c. source with a no-load voltage of no more than 12 V. The voltage drop is calculated between these two places for each exposed conductive component. Between any exposed conductive part and the earth-circuit connection, the resistance determined by measuring the voltage drop and current must not be greater than 0.1 Ohm. There needs to be a lead-through protective conductor for a class II charger.
- **Identifation of protective conductor electrical continuity:** The AC electric vehicle charging station must keep an eye on the electrical continuity of the protective conductor leading to the electric vehicle when charging in mode 3. The electrical supply circuit to the vehicle must be opened by the AC electric vehicle charging station if it notices a loss of electrical continuity of the protective conductor.
- **Breaking Capacity:** For safety reasons and avoidance of component damage, due to disconnection under nominal current, the plug, inlet, connector or the socket-outlet should have enough breaking capacity until or unless there is enough breaking capacity of the available switch.

For further clarification and information, IEC 61851-1-22 provides extensive information regarding all the safety precautions and solutions adapted i.e., avoidance or electric shock, IP degrees for the components used.

- **CCS-Combo 2:** Since the DC Fast Charging system using CCS-Combo 2 in EU is a bit different as compared to the AC Charging, here some of the functions of DC charging considering the safety in hand are discussed in accordance to the standard IEC 61851-23 [25]
  - **Protective conductor continuity check:** For isolated systems, if the rated voltage of DC 60 V or higher, the charging station should initiate emergency shutdown within 10 seconds after losing continuity between EV charging

station and EV protective conductor. While for non-isolated systems, when there is a detection of earthing conductor discontinuity, the EV charging system should be disconnected from the AC supply network (main). For such a case if the rated voltage of 60 V or higher, the charging station performs emergency shut down with in 5 seconds of discontinuity of protective conductor between EV and charging station [25] (6.4.3.2).

- **System De-energization:** If the control circuit of DC charging station fails, it should terminate the supply of charging current and discontinue the supply of control circuit, also, the conductor with the earth fault or overcurrent must be disconnected from the power supply [25] (6.4.3.4).
- **Insulation test before charging:** It is required for the EV charging station to verify the insulation between the the DC output circuit and protective conductor to the vehicle chassis, before the closure of the EV contactors. If the requirement is not met, the charging station sends the signal to the vehicle that the charging is not possible [25] (6.4.3.106).
- **Battery over-voltage protection:** In the case of battery over-voltage i.e., the output voltage exceeds the maximum voltage set by the vehicle, the EV charging station must perform an emergency shut-down and disconnect from the supply. For more information, IEC 61851-23 Annexes AA, BB and CC shows specific requirements for the detection and shut-down.
- **Vehicle connector voltage verification:** The DC charging cable shall not be energized with the charging current in case of the vehicle connector being unlocked, and also the unlocking of the connector should be down below 60 V [25] (6.4.3.108).
- **Short circuit test before charging:** Before the EV contactor is closed, the off-board system should check for short circuit between DC output circuit positive and negative for the cable and vehicle coupler [25] (6.4.3.110).
- **Temporary over-voltage protection:** No voltage greater than 550 V for more than 5 seconds should occur for the charging stations operating at maximum voltage of 500 V either on DC+ PE side or DC- PE side. And for stations between 500 V - 1000 V, voltage greater than 110% of the DC voltage amount should not happen for more than 5 seconds. Further cases i.e., above 1000 V is mentioned in the [25] (6.4.3.113).
- **Protection against electric shock:** The requirements and precautions mentioned in the IEC 61851-1 are applicable for the DC fast charging as well, but Part 23 includes further more protection criteria since the voltage

Limit	Frequency
1.5 A	below 10 Hz
6 A	below 5000 Hz
9 A	150000 Hz

Table 4.7: Current ripple limit of EV charging station

and current for charging is higher as compared to that of the AC, hence requiring higher level of protection. The section [25] section 7 includes the further requirements for the protection against electric shock such as disconnect EV from the supply, if the voltage between the conductive parts and conductive parts is more than 60 V DC, and also the stored energy available is less than 20 J, conditions for the disconnections of Station from the supply mains is mentioned in section 7.2.3.2. Part 23 further mentions protective measures for DC EV charging stations.

– **Current Ripple:** The current ripple of charging station must not exceed the current regulation as defined by the following table 4.7 where the limits defined by the standard [25] (101.2.1.5) are the difference between positive and negative peak.

– **Voltage ripple in CVC:** For CVC, the maximum voltage deviation should not exceed 5% of the requested voltage during the pre-charge state and charging state. And the maximum voltage ripple should not exceed 5 V of the nominal one. While the maximum voltage slew rate should not exceed 20 V/ms [25] (101.2.1.6).

– **Load Dump:** In any case scenario of load dump, the overshoot of voltage should not exceed the limits as mentioned in the Annex AA, BB and CC of the IEC 61851-23 [25].

Communication and Signaling Protocol

- **Type 2 (AC Charging):** For serial data communication, it is an optional task for mode 1, 2 and 3 i.e., AC modes, while for the mode 4 i.e., DC is a different story explained in CCS-Combo 2 section [24], 6.5. Considering the connection between the Power supply and the EV, the clause 8.1 in IEC 61851-1 provides the extensive idea of the physical conductive electrical interface requirements between the EVSE and the EV itself.
  IEC 62196 Protocol [28]: The proximity pin (PP) is a pin which has a simple resister between PP and ground, and based on it the EV and EVSE detects

the maximum amount of current the cable can conduct in order to avoid cable overloading. The PP value is fixed, while the communication between the vehicle and the station is done via Control pin (CP). At first, there is just +12 V between CP and ground, while as the car is plugged in, this 12 V indicates that the vehicle has been plugged in, initiating the actual communication with 1 kHz PWM signalling. For Type 2, it ranges between +12 V and - 12 V controlled the charging station throughout the charging process of the EV, in short, the communication between EV and Charging station is done by the PWM signal through the CP. For more information and details of the communication and signalling process of Type 2, IEC 62196 [28] provides in-detailed description on it.

- **CCS-Combo 2 (DC Fast Charging):**

  The communication between the DC charging station and the vehicle is established by means of basic communication and high level communications. In basic communications such as, initiating charging process, emergency shut down are done by the control pilot lines that exchange signals between the DC station and the EV. While the high level communications are used in order exchange the control parameters for the charging process between the charging station and the vehicle i.e., also known as digital communication (CAN over dedicated digital communication and power line communication (PLC) over control pilot lines) [25] (102.1). The specific requirements for the communication of charging process for DC charging station and EV are given in IEC 61851-24. Also to note as mentioned before the control pilot functions can be achieved by using PWM pilot control.
  Charging control process of an EV through DC charging consist of three steps, namely:

  - Initialization (before charging)
  - Energy transfer (during charging)
  - Shutdown (after charging)

  Initialization: For charging control, it is necessary for the EV and the DC charging station to share all the information regarding the operational limitations and all the relevant parameters. Also, circuit voltage is measured to ensure proper connection of the batteries with the station before initializing the charging process and also disconnection after the end of the charging process. The charging does not proceed forward until or unless the compatibility is tested between the EV and the DC station. After that, EV station verifies the insulation test between the DC power lines and the enclosures, which also includes the vehicle chassis [25] (102.5.2).

Energy Transfer: In this part, there is a continuous communication between the vehicle to the EV station regarding setting up the charging current value or voltage depending on two different algorithms i.e., Constant Current (CCC) and Constant Voltage (CVC). The description of the two processes are described in 2.3.2 2.3.1 while the communication protocol is described in detail in [25] (102.5.3).
Shutdown: When the EV's battery reaches a certain threshold or when the the user stops the charging process, the algorithm processes a normal shutdown, while under fault conditions, the emergency shutdown is processed. After a normal shutdown, the EV and the station configures themselves to return to normal conditions so that the users can safely handle the charging components i.e., cable and connector. Complete description of this process is described in [25] (102.5.4).
The synchronization of the DC station and the EV with each other is done by the following signals and information:

- Through pilot wire circuit
- Through digital communication circuit
- Measurement values through DC charging circuit

The charging control process and general sequence diagrams are specified in the IEC 61851-23 Table 103 and Annex AA, BB, CC respectively, while the digital communication parameters, formats, and other communication requirements are given in IEC 61851-24.

Considering the digital communication architecture as described by the [26] (5), the standard utilizes two communication signalling techniques:

- Based on CAN, protocol given by ISO 11898-1
- Based on Home-plug Green PHY through control pilot line

4.2.2 SAE Standards

Description

Society of Automotive Engineers (SAE) is based in United States, which is a professional association working on the development of standards for engineering bodies in various different industries. Some of the standards related to the interest of this thesis topic are given below in Table 4.8 [11].

Standard	Description
J2293	EV and off-board EVSE requirements from utility grid charging
J1772	Conductive charging standard
J1773	Wireless charging standard
J2847	Communication between EV and utility grid, and off-board charger
J2836	Use cases for A/D communication between EV and utility grid
J2931	Digital communication between EV and utility grid
J1766/J2344/J2578	Safety requirements for charging

Table 4.8: SAE Charging Standards

- **SAE J2293:** It consists of the off-board charging equipment standard. It consists of two parts, part one focuses on the power requirements and overall architecture used i.e., AC, DC or wireless charging strategy, while part two main theme is the communication requirements and network for EV charging.
- **SAE J1772:** It takes into consideration the equipment ratings of the EV charging system. This standard is well designed for both AC and DC charging strategies with charging levels defined in the next section.
- **SAE J1773:** Reqiurements for inductive charging process is well defined in this standard. Since it is out of the scope of this research paper, further discussions are avoided.
- **SAE J2847/J2836:** For the communication requirements between EV and charging infrastructure, these two standards are well defined. J2847 highlights the communication requirements while the J2836 refers to the case studying and testing infrastructure requirements.
- **SAE J2931:** The digital communication between the EVs, EVSE, utility grid and more components is defined in this standard. In order to set up the communication network in smart grid environment for EV charging, this standard requirements must be fulfilled[11].

The main focus will be on the SAE J1772 (conductive charging), SAE J2847/J2836/ J2931 (communications requirements), and SAE J1776/J2344/J2578 (safety requirements).

Charging Levels

Today, SAE J1772 covers the general physical, electrical and performance requirements for the conductive EV charging strategy in North America. The standard categorizes and classify as in the Table 4.9 as a function of rated power, voltage and current [49].

Method	Supply Voltage	Maximum Current	Maximum Power	Charging Phase
AC Level 1	120 V	12 A-16 A	1.44 kW-1.92 kW	1-phase (on-board)
AC Level 2	208 V-240 V	30 A-80 A	7.7 kW-19.2 kW	1-phase (on-board)
DC Level 1	50 V-1000 V	50 A-80 A	50 kW -80 kW	3-phase (off-board)
DC Level 2	50 V-1000 V	50 A-400 A	50 kW -400 kW	3-phase (off-board)

Table 4.9: J1772 (2017) Charging Ratings in North America [17]

- **AC Level 1:** This charging method considered to be the slowest one making use of 120 V with 12-16 A current in single-phase charging. This charging level is typically used at residential and office spaces, also no additional infrastructure is required.
- **AC Level 2:** This utilizes either single or three phase charging with nominal voltage of 240 V that can charge up to maximum current of 80 A hence up to 19.2 kW of power rating, also it is required a dedicated equipment for home (wallbox) or public charging with on-board charger used. Installation cost varies around 1000$ to 3000$ [35].
- **DC Level 1:** This is the fastest charging method and is usually installed for public usage since it requires high cost for installation and maintenance. It utilizes voltage rating of 480 V typically with three phase off board charger. The main idea behind the DC charging is the bypassing of the on-board charger and charging station directly through off-board charging provides the DC voltage to the battery through DC connector [49].
- **DC Level 2:** This is also known as ultra fast charging level since it can reach up to 400 kW of power ratings estimated to charge the BEV completely with 10 minutes from SOC 20% to 80%. Cost for the installation of DC fast charging stations varies between 30,000$ to 160,000$ [35].

Charging Couplers

SAE J1772 describes the standardized connector for the charging AC Level 1 and 2 i.e., Type 1, while for DC Level 1 and 2 the connector used in the North America is CCS-Combo 1. Following the two couplers are discussed in detailed manner.

- **SAE Type 1 Coupler:** The vehicle connector also known as J plug or Type 1 connector consist of 5-pin structure, that uses single phase with AC supply hence used for AC Level 1 and Level 2, hence the AC supplied current is then converted to DC current by the on-board charger in order to recharge the battery[67]. The Figure 4.8 depicts the charger with the vehicle inlet [13].

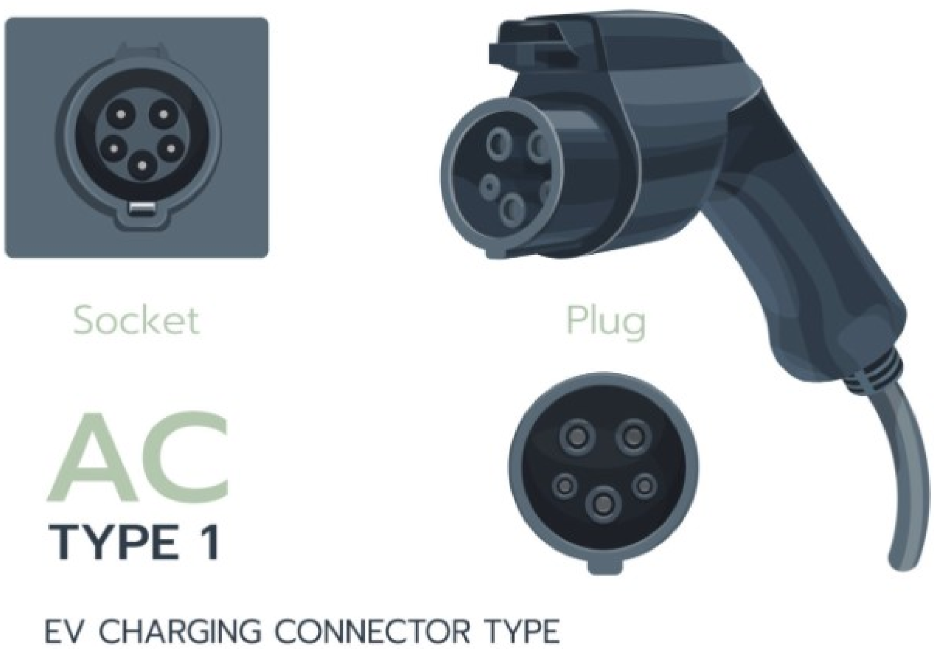


Figure 4.8: J1772 Type 1 Vehicle connector (*right*), Vehicle inlet (*left*) [13]

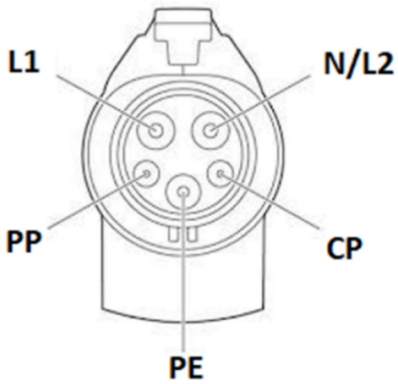
J1772 connector is designed for single phase AC current with 120 V to 240 V used in North America, that consist of five pins and each of the pin is described here:

  - **L1:** It is the AC Line 1 to supply the single phase current.
  - **N:** It is the neutral pin for 120 V AC Level 1 charging or L2 i.e., AC Line 2 for Level 2 charging.

- **PE:** It is protective earth used for safety purposes as described also in the section previously.
- **PP:** It is known as Proximity Pilot i.e., also the one used in the IEC standard connector, which generally provides a signal to the vehicle's charging control system in order to avoid movement of the connector when connected and charging the vehicle through EVSE, and also it is connected to the latch release mechanism to pass on the signals of connection or disconnection.
- **CP:** Also known as communication pilot, used for communication purposes between the EV and the EVSE. As discussed before, the signalling is done by 1 kHz square wave within a modules of 12 V originating from the EVSE, taking control of the entire charging process.

The Figure 4.9 [67] indicates and depicts the J Plug pins layout.

Further safety standards, communication between the EV and EVSE, signalling, and the charging procedure are discussed in the next sections.



- o **L1** : AC single-phase Line 1
- o **L1/N** : AC single-phase Line 2 or Neutral pin
- o **PE** : Protective Earth
- o **CP** : Control Pilot (Post-insertion signaling)
- o **PP** : Proximity Pilot (Pre-insertion signaling)

Figure 4.9: J1772 Type 1 Vehicle connector and the pin layout [67]

- **CCS-Combo 1:** This system is based on SAE J1772 standard/regulation [8], which combines single-phase with rapid three-phase charging utilizing AC with a maximum of 43 kW, on the other hand, when DC charging is used, it can charge with a maximum of 200 kW, while in future the target is to reach around 350 kW. Currently in market, the maximum offered by most of the competitors goes up to 100 kW to 150 kW [31].
The Combined charging system includes all the functions, including control functions, and communication necessary between the vehicle and the infrastructure. The key features of CCS Type 1 includes the electrical interface specifications

for the transfer of power, also the safety features related to DC charging in accordance with the IEC 61851-23 [31, 25]. Also considering the communication interface between the EV and the EVSE, it is based on the ISO/IEC 15118 and the DIN SPEC 70121 [31]. The Figure 4.10 depicts the standard used for AC charging and DC charging and the communication protocol for the CCS Combo 1 and 2. The Figure 4.11 indicates the CCS-Combo 1 using the J1772 standard, normally utilized in the US EV market [66].

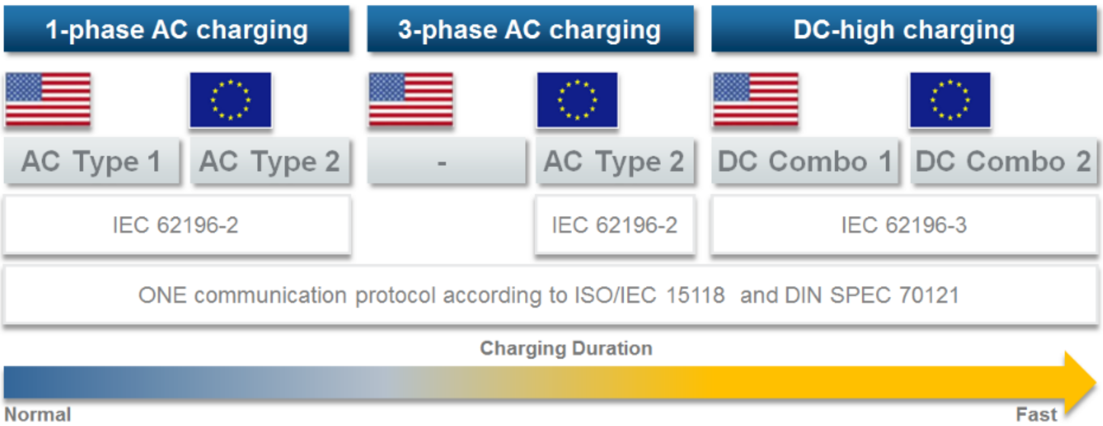


Figure 4.10: Standards for CCS [31]

Figure 4.11: CCS-Combo 1 Connector used in North America

The charge inlet ensures a proper protection for safe and reliable charging, with a lock system to prevent accidentally pulling the connector while charging. It also features automatic digital communication through the PLC between EV and the EVSE, which enables to control more complex charging scenarios like compensating schemes and power spikes i.e., renewable-energy related [31].

Safety Aspect

- **J1772 Type 1:** Multiple stages of electric shock protection and safety features are put forward by the standard ensuring high level of safety in wet conditions also. In order to ensure that physical contact occur with the user, the connection pins are located in the interior of the connector when mated. Even if the connection does not happen, J1772 ensures there is no power at the pins, in short, the pins are not energized until or unless connected and commanded by the vehicle. As mentioned before, the proximity detection pin (PP) is connected to a switch (release button) in the connector. The flow of the charging current is halted once the release switch is triggered. The same phenomena as of the IEC 61851 Type 2 is applicable here, the control pin i.e., of shorter length disconnects first, which disables the EVSE power supply to the plug, also ensuring that the power pins i.e., L1 and L2/N are not disconnected under load, which can endanger user safety, causing arcs and also shortening their life cycle. The ground pin is the longest, that connects first when plugging in, and disconnects the last when unplugged [67].
- **CCS-Combo 1:** The CCS Combo 1 uses various safety measures to avoid, electric shock, fire, and electric arc either in normal use i.e., operation or in non-operational mode. The safety features for CCS have already been discussed in the previous part which take into consideration IEC standards.

Communication and Signalling Protocol

- **J1772 Type 1:**
  - **Signaling:**

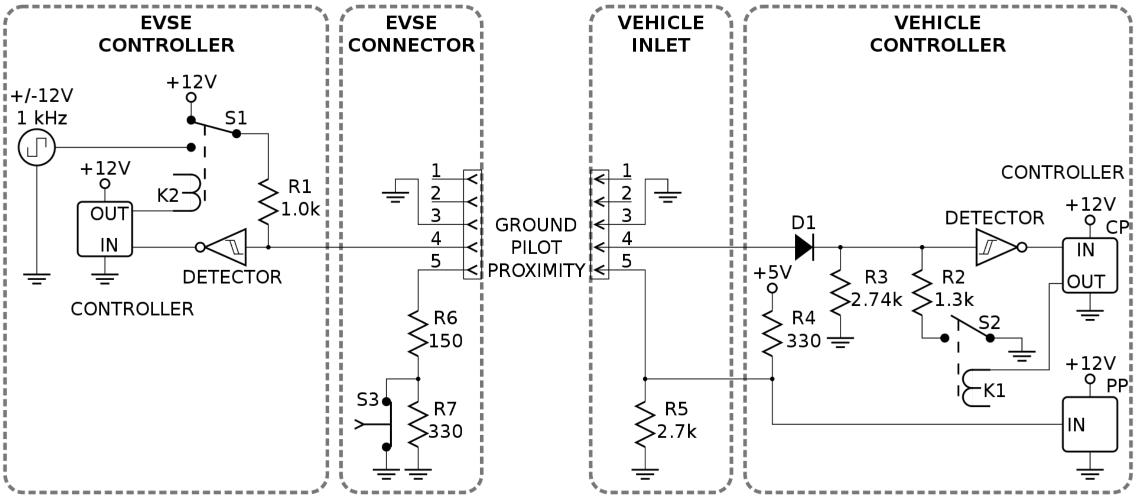


Figure 4.12: J1772 J1772 Signaling Circuit [67]

The Figure 4.12 indicates the the signaling circuit according to J1772 Standard, and it has been typically designed for the following sequence of charging:

1. EVSE signals in presence of AC input power
2. EV detection of the plug through the PP pin and also the detection of latch when connecting or removing of the plug
3. CP controlling signals
4. Vehicle commands energy flow
5. Vehicle and EVSE both considers the safety ground and monitor it
6. Charging current to charge the vehicle
7. Signal to interrupt the charging by disconnecting the plug from the vehicle

This signaling protocol is robust and operable since it does not require integrated circuits as other protocols do. For more specifications description the 2001 version of SAE J1772 and IEC 61851-1 and IEC TS 62763:2013 can be looked into [67].

– **Communication Protocols:** SAE J1772:2023 standard put forward the usage of power line communication i.e., IEEE 1901, that is the communication between the EV, EVSE and the utility grid, which also does not require the usage of an additional pin. P1905 communication protocol is also coherent

with the 802.x standard through the IEEE 1905 standard, which ensures IP based communication with the vehicle, distributor and the location where the charging is being done. It also has wireless communication capabilities and the implementation is being done between the off-board DC EVSE and EV through the CP pin of the J1772 connector through the PLC i.e., HomePlug Green PHY power line communication [67].
The CP is the core controller in order to ensure reliable operation between the EV and EVSE, the control pilot performs, the verification of the vehicle connection, EVSE standby state, EVSE ready-state for the supply of the energy, EV ready-state for energy acceptance from the EVSE, control over proper indoor ventilation and also to check EVSE current capacity.
Digital communication for AC level 1 and level 2 charging is optional at any valid CP duty cycle. While the SAE J2847-1 indicates all the necessary requirements for the communication between the EV, EVSE, and the utility grid. The main purpose of this standard is to optimize the transfer of energy for the EV, while keeping in mind proper enough energy transfer to the EV and avoiding excessive stress upon the utility grid. It also provides guidelines for the vehicle involvement in the grid charging plan or at home area network.

- **CCS-Combo 1:** The DC CCS supports only high level communication which is based on the Power line communication (PLC) since it is needed to control the external DC Charger. The following Table 4.10 highlights the features of a CCS-Combo System.

CCS-Combo 1 Features	
Charging Type 1	DC HLC
Charging Connector	Combo 1
Charging Mode	Mode 4
Load Balancing	Reactive
Charge Authorization Mode	EIM

Table 4.10: Features of CCS-Combo 1 [31]

5 EV DC Fast Charging Process

This chapter presents impact analysis of the two standards i.e., IEC 61851 and SAE J1772 on the charging process specifically considering the technical and practical point of view. 5.1 presents the IEC 61851 DC fast charging sequence for a normal start up currently used in EU, while the 5.2 showcase the charging sequence as of the SAE J1772 utilized in North America (NA). Further in 5.3, there is comprehensive and detailed comparison of the standards mainly focused on the charging sequence, safety features and communication protocols and their impact on the charging process technically and practically.

5.1 IEC 61851-23 Charging Sequence - European

IEC 61851-23 [25] defines different states of the control pilot pin (CP) connection process between the EV and EVSE as presented in the IEC 61851-23 Annex CC **DC EV charging station of system C - CCS**. These states helps in noticing the flow of the current, communication between the EV and EVSE and safety checks throughout the charging process. The table 5.1 indicates the different states and their respective meaning in the whole charging process.

Transition states	Description
State A	Vehicle not connected
State B	Vehicle connected and start of request
State C	Vehicle connected and charging
State D	Connected, charging with ventilation required

Table 5.1: State transition table of charging process (CCS)

For a normal startup of a DC fast charging as described by the IEC 61851-23, the following figure 5.1 shows the charging sequence and the activities related to it as described in Annex CC of IEC 61851-23 [25]. While in the following, for better understanding follows a step by step charging sequence description as per the figure 5.1

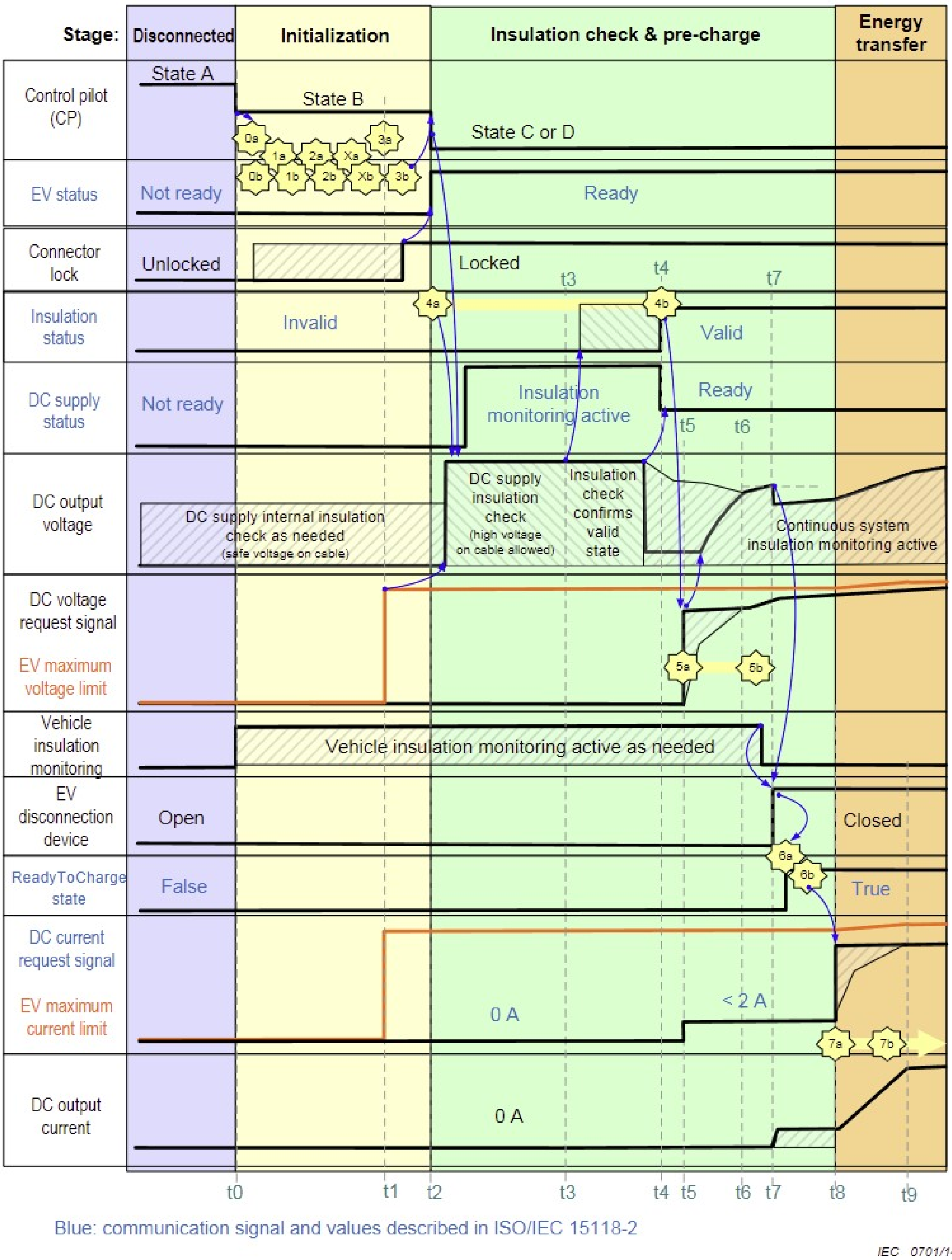


Figure 5.1: EV normal charging sequence startup according to IEC 61851-23 [25]

- **Initial Setup (t0):** As the figure suggests, the CP state A (disconnected) changes to state B.
- **Initialization (t0 - t1):** Communication between the EV and EVSE starts to

establish, exchanging control parameters and also the DC supply verifies if the output voltage is less than 60V, if in case it is greater than 60V, the charging process is terminated.

- **EV Maximum Limits Check (t1):** At t1, the EVSE receives the maximum supply current and voltage limits of the EV.
- **Connector Lock (t1-t2):** The connector is locked and the EVSE responds back to the maximum supply current and voltage limits provided by the EV, insulation checks are also performed without the application of voltage, if in case the EV and EVSE are not compatible, the 'ready' state transition will not occur but it will process the shutdown sequence instead.
- **CP State Change (t2):** At time t2, the EV makes the CP change from State B to State C or D with S2 closing and EV status going to 'ready' state.
- **Cable & Insulation (t2-t3):** There is an insulation and cable check request from the EV after the connector lock is confirmed, and also, EVSE constantly monitors the high voltage insulation and communicates the status continuously.
- **Insulation Status Check (t3):** The EVSE makes sure that the insulation resistance stay above 100 kohm.
- **Cable Check (t3-t4):** After insulation check, Insulation check confirms valid state.
- **Pre-Charge Phase (t4-t5):** The EV sends a pre-charge request containing the information of DC current < 2A and requested DC voltage.
- **Adaptation of Voltage (t5-t6):** As per the EV request, the current is limited to 2A while the EVSE adapts the output voltage to the requrest EV value.
- **Voltage Tolerance (t6):** As indicated in the figure, the Dc output voltage reaches its limit with a tolerance. The EV can also stop the internal insulation monitoring if required.
- **Adjusting Voltage (t6-t7):** For safety concerns of the EV battery, the EV can send signals to adjust the DC voltage in order to minimize the deviation from the EV battery voltage.
- **EV disconnection device closure (t7):** The EV disconnection device closes as soon as the deviation of the voltage is less than 20V.
- **Request of Power Delivery (t7-t8):** The EV signals the EVSE for the power delivery to enable the power supply for charging. The EVSE also disables the pre-charge circuit and make ready the energy transfer.

- **Energy Transfer (t8-t9):** The DC current request is set by the EV to initiate the EV charging process, while the EVSE adapts itself to the requested current and voltage, while continuously reporting the current information to the EV. The EV can also change its current and voltage request during the charging process.
- **Energy Transfer Phase (t9):** The EVSE reaches the EV requested current level with a defined delay time and depending on the charging strategy, EV constantly adapts the current and voltage request.

5.1.1 Effect on Charging Process

Considering the initial start up and the charging sequence of the European IEC 61851-23, it has several implications for the DC fast charging process. These effects can be categorized into different groups, namely, efficiency, user experience, safety and infrastructure.

Efficiency:

Considering the EV HV Battery, the pre-charge phase i.e., t4-t5 where the DC output voltage and current are gradually increased, helps to maintain the efficiency of the battery while also protecting it and other charging equipment. Hence, this phase not only provides higher efficiency but also increases the durability and age of the battery because of smoother transition to the maximum limit of power delivery to the EV. Also, as described by the normal startup procedure, the standard authorizes the adjustment of voltage and current request by the EV which optimizes the fast charging process taking into consideration the current state of the battery and EV itself hence, increasing the overall efficiency.

User Experience:

To ensure reliable and predictable charging times, the standard has a detailed process. This process ensures that the vehicle is ready to charge and also there is a proper increase of power delivery leaning towards a consistent and well-mannered user understanding. Also, users are well notified about the charging process and status due to high level communication between the EV and EVSE, including any potential errors that can arise and terminate the process which directly influences positively the user trust and satisfaction level.

Infrastructure Demand:

Due to high level communication and safety requirements, the infrastructure must be equipped with advanced control systems and equipment, giving rise to complexity and cost increase but on the positive side, certified safety and efficiency. Also, considering the harsh requirement of insulation resistance and DC supply current and voltage limits, it is essential to make use of high-quality equipment in EV and EVSE, reducing the risk of error and failure but largely impacting the cost. Finally, since IEC 61851-23 standard ensures uniformity and compatibility of the EV and EVSE within Europe, it helps to increase the adoption and usage of the charging network.

Safety:

Concerning the safety protocols, the charging sequence according to the standard ensures that there is proper insulation checks before and during the charging process, making sure it does not lead to short-circuit or any other harm to the EV, EVSE or the user, hence, preserving the safety and protection of the vehicle and EVSE. With Maximum current and voltage limits, the continuous communication between the EV and EVSE make sure that the charging equipment operates within the safety parameter range, decreasing the threat of overheating of the Battery or any other related issues that could certainly cause failure or fire. Lastly, the one step at a time initiation of the charging process ensures that the safety checks are completed and comply with the safety standards of the IEC 61851 ahead of high energy transfer to the EV, which includes, proper connection, locking of the connector, insulation check, hence, averting impulsive or not reliable power transfer.

Within Europe, the standard is being continuously monitored and updates are being done in order to ensure proper safety of the equipment and user, while also taking into consideration the complexity and cost. While the current adaptation has been vividly improved as of the previous ones, necessitating advanced infrastructure with high quality components ensuring high level compatibility and reliability within Europe.

5.2 SAE J1772 Charging Sequence - North American

According to the SAE J1772 Standard Appendix F (DC EVSE & EV Charging Sequence & Response Time Specification) [29], A normal charging process consists of three stages, i.e., Handshaking which is the initialization of the charging process, Energy Transfer and Normal Shutdown.

Handshaking:

It is a phase in which the EV exchanges information such as the operational limits and the charging parameters with the EVSE, similar to the IEC 61851 standard specifications, the exchange of current and voltage limitations is necessary, followed by the compatibility check. Moreover, if the compatibility check succeeds, the EV locks to the vehicle inlet the connector, otherwise, the incompatibility is visualized to the customer either on the EV display or by the EVSE. In order be sure that no damage is done to the pins of the EV contactors, the voltage of the EVSE should be controlled and measurable by the EV. Voltage differential could damage the contactors on the EV side. When the contactors are welded, finger proof vehicle inlet pins could be exposed to high voltage. Using the EV maximum voltage limit, the EV controls the pre-charging process. The EVSE provided power helps to reduce the difference of the voltage between the EV RESS and EVSE output and when the voltage difference is within acceptable range, the EV locks the contactors to connect completely the EVSE output to the RESS.

Energy Transfer Phase:

It is initiated when the steps above are done, in which the EV and EVSE constantly exchange and monitor the charging process by taking into consideration the voltage and current readings separately to ensure that they stay within limits. EV may or may not reduce the voltage or the current for the safety and protection of the RESS. The two energy transfer mode that could be used are bulk charging and full charging. In bulk charging, in which the request of the EV is for the energy transfer near to the limitations of the charging process, which goes on for the entire charging session time, and when the bulk threshold has been reached, the EV cuts down the charging session or reduces the consumption in order not to overload the RESS (fully charge the battery). While in full charging, the charging process is controlled by the EV in order to ensure the safety of the battery, which can continue for several hours.

Normal Shutdown:

It is initiated when the EV detects that the charging is finished, by sending communication to the EVSE, which reduces the energy transfer close to null, and finally opening the charging contactors of the EV, hence initiating normal shutdown phase. It occurs when the battery (RESS) reaches a certain/desired SOC helping to retain a certain safe condition so that the customer can remove the connector from the vehicle inlet.

The safe condition is that the current is close to zero, which in-fact opens the on-board contactors and let the inlet voltage drop to a safe threshold i.e., smaller than 60 VDC as defined by the SAE J2344, the connector unlocks so it can be detached by the customer from their vehicle inlet.
Considering a normal startup sequence as for the European standard i.e., IEC 61851-23 discussed previously 5.1, here it is described in detail in Figure 5.2 the normal charging startup sequence according to the SAE J1772 Standard.

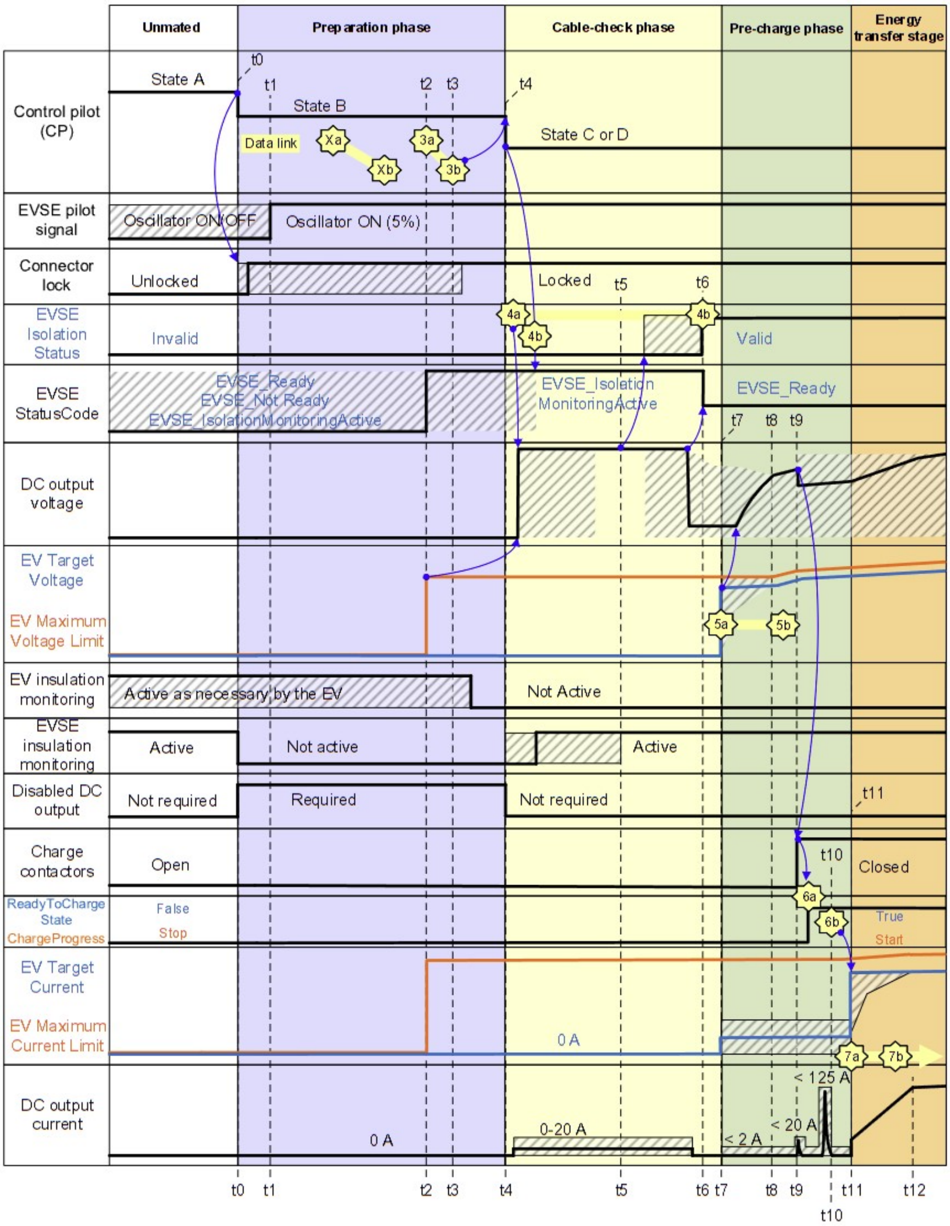


Figure 5.2: EV normal charging sequence startup according to SAE J1772-2024 [29]

- **Unmated (t0):** The DC output voltage between the DC+ and DC- remains smaller or equal to 60 V DC. And also the Control Pilot signal is at state A, with EVSE Pilot Oscillator off, connector unlocked, EVSE Isolation status invalid, with EVSE StatusCode Not Ready.
- **Preparation Phase (t0-t1):** In this transition, CP moves from State A to State B, while the oscillator remains off, and the connector locks depending on the compatibility and limits check between the EV and EVSE, and also the EVSE insulation monitoring not active within this period, reqiuring to disable the DC output.
- **Preparation Phase (t1):** EVSE turns on the CP oscillator if the EVSE is ready for the transfer of energy or if the CP oscillator is not turned on yet. The EVSE also maintains the duty cycle of 5% from the start of the data link at t1 till the communication ends, or if a certain duty cycle is required depending on the different conditions.
- **Preparation Phase (t1-t2):** Digital communication starts by communication protocol layar between the EV (Xa) and EVSE (Xb), exchanging information like setup, services, authentication, payment option etc.
- **Preparation Phase (t2):** EV sends the maximum voltage limits and maximum current limits, also some other parameters to the EVSE with the communication signal (3a).
- **Preparation Phase (t2-t3):** Then the EVSE performs further the compatibility check with the EV. The EVSE checks if the voltage at the DC output is smaller than 60 V DC. The EVSE sends the EVSE maximum voltage and current limits back in a message communication to the EV with (3b). In this message the EVSE Status Code i.e., EVSE_IsolationMonitoringActive is also sent.
- **Preparation Phase (t3-t4):** If the EV and EVSE are not entirely compatible after the compatibility check, the EV performs error shut down in this phase, further information can be seen on the standard F.1.10.1 [29]. Otherwise the EV shall lock the vehicle connector to the vehicle inlet before moving to the cable check phase i.e., State C or D. Also in this phase the vehicle deactivate the EV insulation monitoring (IMD), only if the compatibility between the EV and EVSE turns out to be positive.
- **Initiation of Cable Check Phase (t4):** After the IMD disabled and connector locked, the EV moves from the State B to State C or D by locking S2.

- **Cable Check Phase (t4-t5):** With the (4a) communication message, the EV requests the cable check phase before starting the pre-charging phase. The EVSE checks then if the CP changed to state C or D then sends back the signal (4b) before the DC output voltage increases than 60 V DC. In this phase, the IMD can be activated while after the t4, the DC output voltage is disabled. The DC output current increases from 0 A and limited to within 0 A - 20 A current threshold.
- **Cable Check Phase (t5):** At this timestamp, the EVSE determines that the DC output insulation resistance is greater or equal to 100 kohm (F.1.9).
- **Cable Check Phase (t5-t6):** The EVSE checks the IMD functioning and also the insulation of the DC output and continuously reports the insulation state with the (4b) message.
- **Cable Check Phase (t6):** After the cable check phase is combpleted, the EVSE launches a message (4b) with the EVSEIsolationStatus and EVSEProcessing 'Finished'.
- **Cable Check Phase (t6-t7):** EVSE may keep the current voltage at the DC output.
- **Pre-charge Phase (t7):** EV sends the signal (5a) with the EV target voltage which depends on the voltage of the battery, hence initializing the pre-charge phase.
- **Pre-charge Phase (t7-t8):** The DC output voltage in this timestamp period ramps up initially while the the EV target voltage stays below the maximum voltage limit considering the safety of the battery while the current target stays well below the maximum limit and the DC output current is smaller than 2 A. The EVSE controls the present voltage at the DC output with respect to the target with the (5a) messages and sends corresponding messages (5b).
- **Pre-charge Phase (t8):** The voltage at the DC output increases until the target voltage is met of the EV.
- **Pre-charge Phase (t8-t9):** The EV senses and adapts to the target voltage with the continuous communication between the EV and EVSE.
- **Pre-charge Phase (t9):** The EV closes and locks the contactors only if the difference between the present voltage at the DC output and that of the battery system is lower than 20 V DC.

- **Pre-charge (t9-t10):** EV can request to deactivate the pre-charge limitations on current by the (6a) message, hence could be seen in the Figure 5.2 that the DC output current peak is lower than 125 A.
- **Pre-charge (t10):** Since now the pre-charge current limitation is disabled and the DC output is enabled, the EVSE sends signal (6b) indicating that the EVSE is ready for the transfer of energy, also the over-voltage protection should be enabled at this stage.
- **Energy Transfer Phase (t11):** With the (7a) message, the EV target current parameter is set initiating the energy transfer stage, which consists of the EV maximum voltage and current limit that must be respected and must be less than or equal to that signals communicated with (3a) message.
- **Energy Transfer (t11-t12):** EVSE respectively adapts itself to the target parameters of the EV sent within the message (7a), and responds back with the (7b) message that contains information of the presents current and voltage at DC output, thresholds and power of the EVSE at DC output and the present status.
- **Energy Transfer (t12):** The current at the DC output reaches the target value of the EV with a certain time delay. And, according to the energy transfer strategy, the EV adapts to the current and voltage by acting on the EV target current and target voltage which is done by cyclic transfer of signals between EV and EVSE with (7a) and (7b) signals.

5.2.1 Effect on Charging Process

Considering the SAE J1772 charging startup sequence, it makes sure that the safety levels are prioritized by executing uncompromising voltage boundaries, insulation monitoring, and secure and safer connector locking mechanism. Looking at the figure 5.2, it does projects highly sophisticated infrastructure with progressive communication and controls increasing interoperability and experience of the user. And also efficiency of the charging process is taken into consideration through charging parameters continuous adjustments and monitoring, promoting an optimal and safer charging procedure initiation.

Efficiency:

This standard implies voltage matching feature that reduces the difference of the DC output voltage to the battery system voltage, which is done before implementing the increment on current, which minimizes the energy loss and increases the energy transfer efficiency in the pre-charge phase. And also the charging parameters are adjusted in real-time meaning that the EV adapts and monitors continuously the target current and voltage depending on the battery state and requirements, which also affects the efficiency. And, charging conditions on the EVSE are also continuously monitored and altered depending on the real-time conditions, maximizing the energy transfer depending on the battery system under charging process.

User Experience:

As discussed above, the communication and signalling is highly detailed with various compatibility checks improving the compatibility of the EVs to be charged at any reliable and fitting charging station, improving user experience and reducing compatibility issues. Also, due to high communication, clear messages are delivered to the users especially considering error codes. And, during the transition process of the start and stop, the charging process is smooth and well-managed.

Infrastructure Demand:

Complex infrastructure that is able to carry fast, reliable digital communication between the EV and EVSE is required for robust data link and monitoring, performing compatibility checks. In North America, usally the infrastructure should be able to support DIN SPEC 70121 standard for high level communication. Since detailed checks are performed on the EVSE side i.e., insulation monitoring, over-voltage protection, pre-charge phase, it has to be supplied with high and advanced monitoring and control systems. Finally, system must be able to handle dynamic current and voltage adjustments depending on the real-time based EV target values.

Safety:

There is a continuous monitoring of the voltage difference between the DC+ and DC- in order for it to be smaller than or equal to 60 V DC before the energy transfer begins between the EV and EVSE, if it exceeds then error shutdown is initiated, resulting in high protection against high voltage exposure, before both the systems are connected in a right manner. Insulation monitoring device (IMD) ensures insulation of DC output, avoiding short circuits, and also helping in avoiding failure during charging process. Also, the EV ensures proper locking of the connector to the vehicle inlet before high current transfer is done in the energy transfer phase, preventing arcing or other electrical hazards. And also as described in the [29], clear instructions on the error shutdown are provided in order to avoid potential hazards from sudden or accidental power cuts.

5.3 Comparison of EU & NA DC Fast Charging Process

5.3.1 Charging Sequence Comparison

Key Features Highlight

Here in table 5.2 the key points of IEC 61851-23 and SAE J1772 are highlighted considering the start up sequence explained in detailed in section 5.1 & 5.2.

<table>
<tr><th colspan="3">Key Points</th></tr>
<tr><th></th><th>SAE J1772
(North American)</th><th>IEC 61851-23
(European)</th></tr>
<tr><td>1.</td><td>State A - Unmated:
- Control Pilot (CP) is off
- Connector unlocked
- Current/Voltage null</td><td>State A - Disconnected:
- Control Pilot (CP) is off
- Connector unlocked
- EV not ready
- No voltage or current</td></tr>
<tr><td>2.</td><td>State B - Preparation Phase:
- Control Pilot Oscillator ON (5%)
- At t1, data link starts
- Locking of connector
- EVSE Status Code = Monitoring Active
- Insulation monitoring check
- Disabled DC output required
- EV maximum current limit signalled</td><td>State B - Initialization
- Control Pilot is on
- Connector locking
- EV maximum voltage and current limits communicated
- EV insulation monitoring active</td></tr>
<tr><td>3.</td><td>State C or D - Cable check Phase:
- EVSE isolation status checked and validation
- DC output voltage > 60 Vdc
- EV insulation monitoring not active
- EVSE insulation monitoring (IMD) active
- Disabled DC output not required
- EVSE ready to charge
- DC output current within 0A-20A</td><td rowspan="2">State C or D - Insulation check & Pre charge
- EV Status 'Ready'
- Insulation status validated
- DC supply insulation monitoring active and ready
- DC output voltage supply
- DC voltage and current requests signals starts
- Ready to charge 'True'</td></tr>
<tr><td>4.</td><td>State C or D - Pre Charge Phase:
- EVSE isolation status valid
- DC output voltage and current gradual ramp up
- EV target voltage and current set up</td></tr>
<tr><td>5.</td><td>State C or D - Energy Transfer
- Monitoring the charging continuously
- Voltage and current adjusted within target limits</td><td>State C or D - Energy Transfer
- DC Output voltage and current ramping within target limits
- Continuous DC output voltage IMD active</td></tr>
</table>

Table 5.2: Key Features of SAE J1772 & IEC 61851-23 Standards

Parallelism

In this section, considering the charging start up sequence, similarities between the two processes are discussed in table 5.3.

Initialization	Voltage check	In both the standards, Vdc <60V required before all the safety and insulation checks are performed and ready to proceed in precharging or charging phase.
	Connectors	The state changes from A to B and in this phase the connector is attached to the EV charging inlet.
Handshaking	Communication	Data link required for the connection and communication for charging parameters information exchange between EV and EVSE, even though the protocol may vary.
	Current/Voltage Limits Exchange	EV sends initally the voltage and current limits to the EVSE, IEC Standard in initialization phase and SAE in preparation phase. And then the EVSE reacts back by sending signals with the compatibility and its ability.
Safety/Protection	Insulation Check	Both have the capabilities to monitor insulation and isolation continuously, and proceed only if the threshold conditions are met.
	Locking Connector	The connector locking is an essential part of the charging safety protocol.
Ready to Charge		Both standards have ready to charge state given by the EV.
Pre-Charge Phase	Variable Voltage	While limiting the current within a certain threshold, the EVSE adjusts the DC output voltage limited by the targets set by the EV in pre-charge phase.
Energy Transfer	Power Request	The EVSE status is 'Ready' once the EV sends the request for the delivery of the power.
	Continuous Current Adjustment	EVSE adjusts the DC output current depending on the response of the EV, keeping in mind the voltage and current limits, battery health, temperature and aging into consideration.

Table 5.3: Similarities between the IEC and SAE Standards

Polarity

Considering the two standards, the table 5.4 points out the differences that both of them have especially during the normal start up phase of the charging process.

	IEC 61851-23	SAE J1772
Initialization	Internal insulation check (safe voltage on cable) and requires the EV status 'ready' at the start of insulation check and precharge phase.	In the preparation phase, it emphasizes on the EVSE pilot signal to be turned on by using oscillator and establishes early data link connection. EVSE status 'ready' priortized before insulation check.
Monitoring of Insulation	Continuous DC supply insulation and monitoring along with EV insulation monitoring required.	EVSE insulation monitoring active during cable check phase while the EV insulation less involved usually inactive during cable check.
Pre-charge	There is gradual increase of the voltage and current in this phase with the requests from the EV <5a> and <7a>.	In this phase it usually emphasize on the current ramping after reaching target voltage.
Signalling Communication	Uses basic states A, B, C, and D and also with specific communication and signallig protocol between EV and EVSE.	It also consists of state A, B, C, and D but emphasize more on the EVSE pilot oscillator with different standard used for high level communication and signalling.

Table 5.4: Differences of the two charging standard startup sequence.

Consequences on Charging Process

The similarities and dissimilarities highlighted above between the two charging standards used further implies their effects on the charging process which is discussed in this section table 5.5

	SAE J1772	IEC 61851	Effect on Charging Process
No. of Phases	5	4	SAE has additional phase indicating more progressive start as compared to the IEC, suggesting more in detail step by step initialization and verification before ramping up thet voltage and current, possibly increasing reliability and safety.
Control Pilot	Both the standard utilizes the CP to communicate the states between the EV and EVSE.		Higher level of compatibility of the EVs with the EVSEs by using CP signals hence higher interoperability.
Status Signalling	Oscillator as EVSE pilot signal.	EV status 'ready' or 'not ready'	IEC has a more of a straightforward procedure since it uses direct indication, while the SAE uses oscillator to indicate EVSE readiness, and this suggests that this would have an effect on how rapidly a system reacts to this.
Connector Lock Timing	Early locking in the 2nd phase.	Locks at the end of the initialization phase.	Locking the connector late in the IEC suggests that it can allow further verification and checks before being sure of locking the connectors completely, while opposite to that SAE implies early locking of the connector to be sure that the connection is secured before beginning other verifications or increasing voltage or current.
Isolation and Insulation Monitoring Validation	Almost at the end of the cable-check phase the isolation status is 'valid'	Almost in the middle of the insulation check and pre-charge phase, the status is 'valid'.	This suggests that the SAE approach requires additional time to confirm before validating the isolation status, which could have a positive influence reducing the risks of faults, while IEC procedure suggests smoother and faster validation.
DC output voltage	Both standards initiates at the same level i.e., zero volts and ramps up with similar structure.		Discussing in details, the ramping process might vary slightly but both the standards ensures that proper safety protocols and precautions are followed before ramping up voltage, but a significant difference is highlighted by the IEC, which has continuous DC supply internal insulation check if needed followed by DC supply insulation check and then insulation check confirms to be valid, giving a signal for DC supply status to be 'ready' which is more detailed when compared with SAE.
Insulation Monitoring	Insulation monitoring of EV only active if required, while for the EVSE, it is only 'not active' in the preparation phase.	It has continuous insulation monitoring.	Constant monitoring of insulation in the IEC standard ensures that throughout the startup whenever a fault occurs, it could be detected instantly, effecting positively the safety. While when considering the SAE, due to in-active in the preparation phase only could have issues with the transient.
Charge contactors	It uses charge contactors to take care of high current supply to for the charging.	It uses EV disconnection device before ramping up the current before the start of the energy transfer phase	Considering both of them, they offer same level of safety, but the control mechanism could influence how quickly or slowly the structure responds to it.

Table 5.5: The differences of the two standards along with their effect on the charging start up process.

In conclusion, the process of startup sequence mentioned by both the standards prioritize safety, high efficiency, interoperability with their separate ways of phase management, signal communication protocols, and monitoring of different parameters throughout the process. In the end, they both could offer a trade-off between level of safety offered to the time required to actually start the charging process.

5.3.2 Investigation Scenarios

DC Output Current Ripple

It is the superimposition on to the DC output current of relatively small fluctuations usually done by the EVSE charging system. The reason for such phenomenon is usually linked to various factors. One of the contributing factors is the rectification in power supply, switches in the power converters used, or the electronic components of the EVSE charger.

When high magnitude of ripple onto current is present, it could increase the heat and stress onto the battery of the EV, which could in fact negatively impact decreasing its lifespan and increasing its degradation. Also, it could result in electro-chemical reactions within the battery, which could inversely reduce the performance and protection of the components. Also, it is important to study this effect since it leaks out efficiency of the entire charging process, hence, less the ripple is, the better is the energy transfer during the charging of the battery, which also has better power quality and operations of the vehicle's electronics. That is the reason why standards dictate limits on to the ripple, since excessive ripple could lead to heating issues, failure of the components or BMS, capacitors and inductors in the power supply chain could be under high stress due to high ripple compromising the safety and functioning of the charging system.

IEC 61851-23 (101.2.1.5)		SAE J1772 (6.5.14)			
Limit	Frequency	Frequency	Current at DC output (I)		
			I ≤ 200 A DC	200 A DC < I ≤ 400 A DC	I > 400 A DC
1.5 A	below 10 Hz	10 Hz	1.5 (2)	I x 0.75% (2)	3 (1) I x 0.75% (2)
6 A	below 5 kHz	5 k Hz	I x 1.5% + 3 (1) 6 (2)	6 (2)	I x 1.5% (2)
9 A	below 150 kHz	150 kHz	9 (2)	I x 4.5% (2)	18 (1) I x 4.5% (2)
the limit is the difference between +ve peak top and -ve peak top at full scale output		Frequency: Cut-off frequency of first order LPF (1) Recommended peak-peak limit (2) Abs maximum peak-peak limit			

Table 5.6: DC Output Current Ripple [25, 29]

The table 5.6 indicates the limits provided by the two standards.

- **IEC 61851-23:** The ripple measurement is done at the maximum power output or worst case scenario i.e., the case in which the output voltage and current originates the maximum possible current ripple. Also, the measurement is done by the difference between the positive peak and negative peak values on full-scale output [25] indicated by table 5.6.
- **SAE J1772:** The table 5.6 indicates that the current ripple is a function of the DC output current range, and its limits are given by the peak-to-peak values. The frequency indicated is the cut-off frequency of the 1st order low pass filter (LPF), i.e., the frequency when the LPF begins to attenuate the high frequency current ripple part. While the table 5.6 also indicates absolute maximum peak-to-peak limit that is the upper limit that must not exceed in order to avoid any further damage to the components of the EV or EVSE. The utilization of the fixed limits and absolute values with different current levels provide high level of compatibility of the EV and EVSE considering different charging cases, it also assures that a balance is sustained between high performance and protection of the components since the absolute limiting values ensures that a margin is maintained for safety purposes while the strict recommended values ensures efficient and better working of the components with higher longevity of the battery [29].
- **Comparison:**
  1. SAE provided a table with an approach that not only consider the recommended limits but also the absolute ones which depends on three different

current levels, while IEC major attention is on the measurement of the current ripple with maximum output power or the worst case scenario.

2. Both the standards cover similar frequency ranges.
3. Both the standards objective is to ensure proper protection of the EV and EVSE components while also taking into consideration performance and efficiency of the charging process. SAE two limitations provide a path way for better handling the balance of safety, compatibility and performance.

DC Output Voltage Ripple

The figure 5.3 [25] (Figure 105) indicates the voltage dynamics that are taken into consideration when studying the voltage ripple and other characteristics.

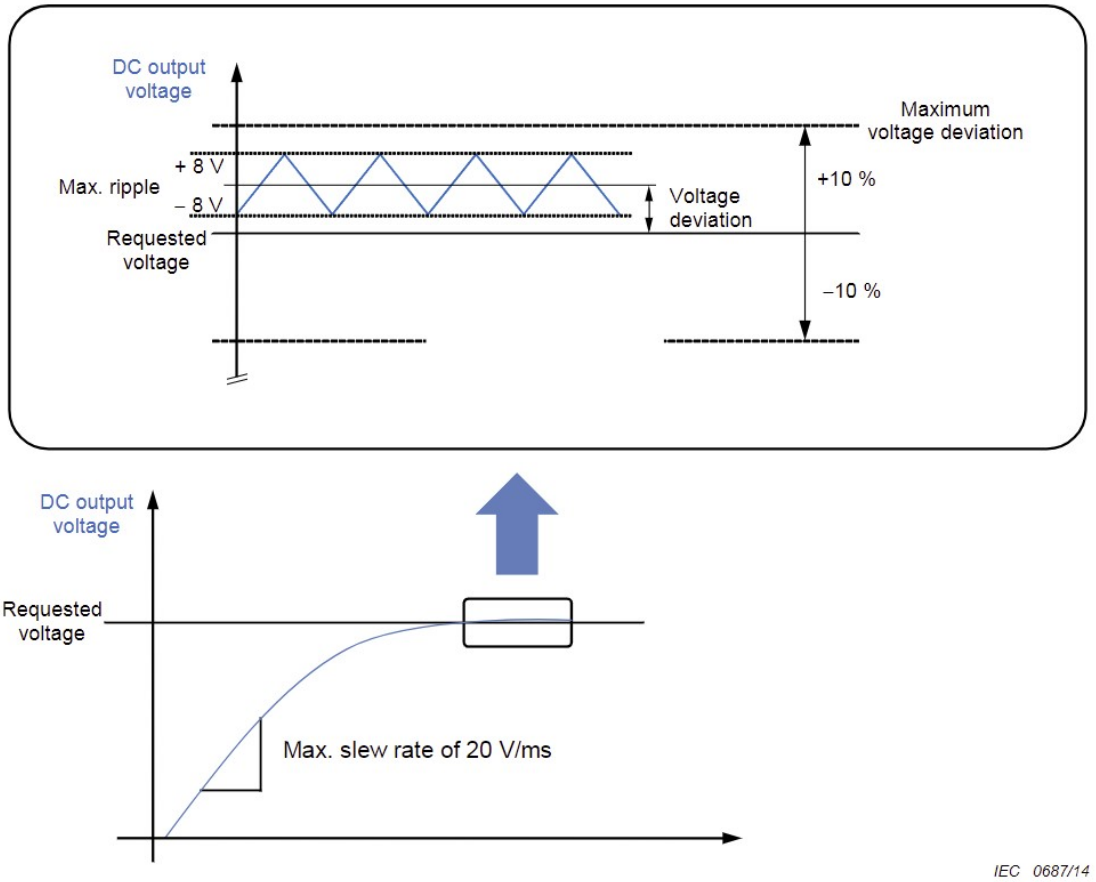


Figure 5.3: DC Output Voltage Dynamics [25]

- **Maximum Voltage Deviation:** As depicted in figure 5.3 the maximum voltage deviation provides a tolerance to the EVSE charger to provide the requested DC output voltage by the EV, enhancing the efficiency and safety of the BMS. The benefit of doing so, is that it prevents over or under voltage than the requested voltage which could result in battery cells to be under stress.
- **Maximum Voltage Ripple:** It is the usual fluctuations of the DC output voltage, it should be limited to a range provided with in a standard so to avoid excessive stress upon the BMS of the EV, also to decrease degradation of the battery and increase the efficiency and performance of the charging process as studied in the current ripple section.
- **Maximum Voltage Slew Rate:** It is usually limited in order to avoid the rapid increase of the rate of change of voltage, that could result in high variation or deviation from the actual target or spike that could destabilize the voltage damaging the battery or the electronic components. Limiting it within bounds, would also keep in tact that the voltage increment is smooth so to have stable charging process.

	IEC 61851-23 (101.2.1.6)	**SAE J1772 (6.5.15)**
Maximum Voltage Deviation	In pre-charge and charging state - should not exceed \± 5% of the requested voltage.	In pre-charge, the voltage should be within \± 5 V with in 2 ms of the requested voltage. In steady state, the margin between the requested and actual voltage must be ≤ 2% of the maximum value of EVSE.
Maximum Voltage Ripple	Normal operating condition - It must not be higher than \± 5 V.	Voltage target ≤ 500 V DC - Voltage Ripple must be with the \± 5 V during pre-charge and steady state conditions. Voltage target 500 V DC - It must be ≤ \± 1% of the target voltage during normal and pre-charging part.
Maximum Voltage Slew Rate	Normal operating condition - It must be lower than \± 20 V/ms.	

Table 5.7: DC Output Voltage Dynamics with regards to IEC and SAE Standards [25, 29]

The table 5.7 shows a comparison between the two standards, while in the following there is a descriptive analysis.

- For the maximum voltage deviation the IEC and SAE uses similar specifications i.e., $\pm$ 5% during the pre-charge and charging states.
- For the maximum voltage ripple, IEC has a fixed limit while for the SAE it is depended on two voltage levels.

- With SAE, the tolerance at voltage > 500 V DC is much stricter as compared to < 500 V DC and it is done by the specific percentage rather than fixing a value as seen in the table 5.7 hence adjusting is proportional and dependent onto the voltage levels.

DC Output Short Circuit Test

- **Short Circuit:** It is usually caused by an accidental link between two points within a electrical circuit, that generates a path way for low-resistance, hence generating a flow of high current. The negative impacts it brings are overheating issues, components damage, and fire hazards. For EV charging, it is essential and necessary to conduct necessary checks in the pre-charging phase for any possible short circuits, especially during fast charging process the checks are performed between the DC+ and DC-. It is necessary for safety and reliability of both EV and EVSE.
- **Importance:**
  1. It ensures that no electrical fires or component harm is done.
  2. Protects EV and EVSE from possible electrical damage.
  3. Helping hand for a safer and smoother charging operation.
  4. Standards work strictly on this specifically in order to promote high safety.
- **IEC 61851-23 (6.4.3.110):** According to the standard specifications [25], the test is conducted when the EV is connected with the EVSE just before the EV contactor are closed. And to check for possible short circuit, the EVSE verifies the voltage between the DC+ and DC- terminals i.e., of the charging cable and of the coupler of the vehicle, i.e., checking any unintentional low-resistence path for the positive and negative terminals, if there is a possible short circuit, the charging process is stopped at that instant, and according to the communication protocol used, safety measures and precautions are taken accordingly. The means of detecting the short circuit should be guided by the EVSE *(under consideration (Annex CC))*.
- **SAE J1772 (6.5.18):** According to the standard [29], the short circuit testing is performed before high voltage DC output is provided by the EVSE. The standard indicates, that the test shall be conducted on the DC+ and DC- terminals of cable used for the charging, connector, inlet of the vehicle, cabling going up to the vehicle DC charger connectors. Detection of the short circuit is done when

the current is around 1 A - 4% of the output maximum current rating, maximum of 20 A. Further as studied in the sequence diagram for DC Fast charging in section F.1.19. [29], after the detection of the short circuit, error shutdown sequence is done, and this sequence communication and signalling protocols are in compliance with either ISO 15118-2:2014 or DIN SPEC 70121:2014. Figure F4 [29] indicates the error shutdown due to the short circuit detection by the DIN SPEC communication protocol utilization preventing energy transfer phase to initiate.

- **Comparison:**
  1. **Testing Procedure:** IEC requires a mean to check for the short circuit *under testing in 2014 standard file* before the closure of the EV contactor. While for the SAE testing procedure, testing is done by the EVSE which checks for short circuits before enabling high voltage DC output and in the standard, it provides detailed sequence for error shutdown.
  2. **Error Detection:** IEC main motive is checking before closing the contactors, while for the SAE proceeds with error shutdown if detected, henceforth rapid response in order to avoid any damage or harm.
  3. **Objective:** IEC checks for short circuit between the DC+ and DC- terminals of the charging cable and vehicle coupler only. While SAE standards defines a current tolerance i.e., 1 A - 20 A (4% of maximum output) checking on the charging cable connector, inlet of the vehicle, DC charger connectors, finally initiating error shutdown procedure based on either ISO or DIN SPEC communication protocols explained in the [29].

DC Output Load Dump

- **Load Dump:** In terms of EV charging, it refers to the sudden disconnection of the EV battery from the EVSE, while other EV loads are still in contact with the EVSE, resulting in overshoot of voltage i.e., spike of voltage increment due to battery disconnection, hence could cause damage to the EV HV battery.
- **Importance:**
  1. By controlling the voltage spikes, damage to the EV and EVSE components can be prevented.

2. Considering the reliability of the process, it is important to make sure that the charging process is able to take control of sudden changes in the voltage without any issue or damage.

3. Both the standards take load dump into considerations, in order to ensure safe working of the equipment and meeting performance objective, and lowering the risk of damaging the electrical and electronical sensitive devices of both EV and EVSE.

- **IEC 61851-23 (101.2.1.7):** According to the standard [25], the scenario defined for load dump is when the output current reduces from 100% (nominal value) to 0% i.e., usually due to the disconnection of the battery from the power supply while all the other loads are still connected. The limit given by the standard is that the overshoot of the voltage should not exceed 110% of the maximum output voltage requested by the EV as indicated for the CCS charger (Annex CC). And, the maximum voltage slew rate of the output voltage when load dump occurs should be with in the 250 V/ms.

- **SAE J1772 (6.5.30):** The criteria defined by the SAE [29] for the voltage overshoot is that, after 3 ms, at the DC+ and DC- terminal DC output voltage is given for two different maximum rated voltages

  – Maximum Rated Voltage > 500 V: Voltage overshoot should be equal or lower than 110% of the maximum rated voltage.

  – Maximum Rated Voltage $\leq$ 500 V: Maximum Rated Voltage plus 50 V.

- **Comparison:**

  1. IEC voltage overshoot limit is 110% of the maximum voltage limit as of the EV request. While general guidelines of various charging configurations are given in the Annex AA, BB and CC. SAE specifies the voltage overshoot limits based on the maximum rated voltage i.e., if it is either smaller than 500 V or if its greater or equal to 500 V. This indicates that SAE lay down specific threshold as a function of rated maximum voltage, which is a more tailored procedure.

  2. IEC indicates a maximum slew rate i.e., 250 V/ms when load dump occurs, while in the SAE standard, there is no direct indication of the slew rate limitations but it does have a voltage overshoot critieria with in set time period. IEC slew rate objective ensures that that the transition phase when the load dump occurs is within control in order to avoid further damage to the components due to exponential increment or growth of voltage.

6 Simple DC Fast Charging Station & High Voltage Battery Modelling

6.1 Simple DC Fast Charging Station

6.1.1 Charging Station Designing

In this subsection, a theoretical approach is provided which further is adopted in subsection 6.1.2. Since, complete or in depth explanation is out of the scope of this research, a brief summarized version of the designing process is explained as done in [3].

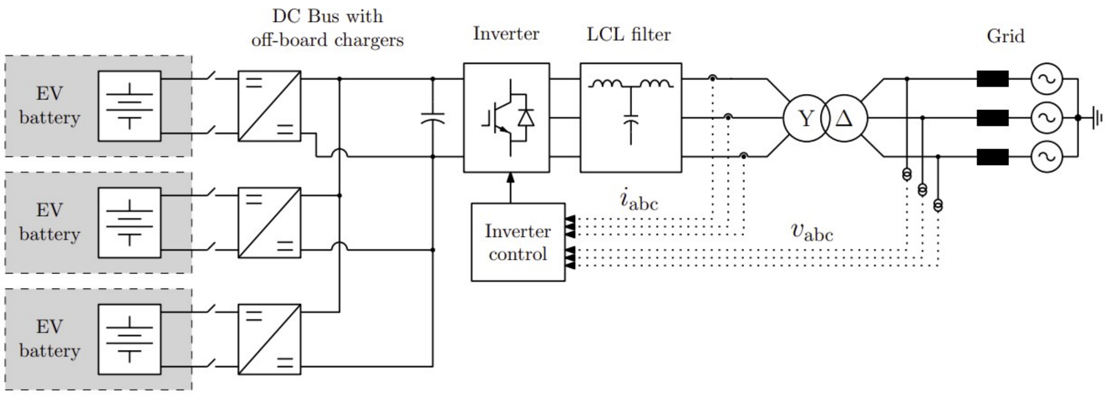


Figure 6.1: DC Fast Charging Station Configuration [3]

The figure 6.1 is the proposed charging station configuration which consist of an inverter connected to a LCL filter, further on to a transformer, while on the other side of the inverter is a single DC bus that feeds all the individual battery chargers attached. For simplicity purpose, the case considered is only one EV battery for charging.

The AC to DC conversion by the inverter from the grid causes harmonics which would directly imply power quality issues, the ***LCL filter*** provides a low-impedance pathway to ground for unwanted harmonic frequencies. While the ***transformer*** is used to regulate or control the voltage levels in between the grid and the inverter, it also take into consideration that the operation is performed safely without or with low as possible voltage fluctuations, providing an electrical isolation between the grid and inverter, hence preventing direct electrical contact between the grid and charging components avoiding electrical hazards i.e., short circuit or shocks/arcs. Also, considering both the LCL filter and transformer, they are utilized for power factor correction, i.e., power drawn from the grid is utilized effectively with low as possible energy losses.

DC Bus capacitance directly influence the stability and the DC current ripple, and the ripple effect increases with increasing EV chargers connection. According to [3], it is calculated by the capacitor energy rate of change during transients and the rated power. ***EV Battery*** used is Thevenin equivalent based model, in which the Open Circuit Voltage depends on the State-of-Charge (SOC), while the series resistance shapes out the voltage current characteristics, and the RC parallel circuit shows the transient response of the EV battery as indicated by the electric circuit configuration of the entire charging station in figure 6.4. ***Battery Charger*** chosen to be is a bi-directional DC/DC converter with IGBT switches as in figure 6.4 in order to achieve a bi-directional power flow. Lower switch operating results in boost operation, while upper switch operating results in buck operation, for more clarification [3] is useful. ***Three-phase inverter*** indicated in figure 6.4 consists of six switches which further connects to the the LCL filter. ***LCL filter*** used is a passive one to reduce grid-interfaced power source harmonic disturbances, for further detailed analysis [48, 4, 58] are useful. The inductance on the inverter side is dependent on the DC voltage, inverter modulation index, switching frequency and current total harmonic distortion (THD), while the capacitance, and inductance on grid side depends on parameters and characteristics of the grid, reactive power, resonance frequency, and ripple attenuation factor (RAF) [3]. ***Control System*** consists of a low level controller i.e., charging station control system and a high level controller i.e., charger control system as explained in [3] and depicted in figure 6.2 & 6.3. Where in high level control i.e., battery charger control, two different strategies can be implemented i.e., constant current (CC) defining the boost-mode operation, and constant voltage (CV) for the buck-mode charging which in the simulink modelling was dependent on the SOC of the battery.

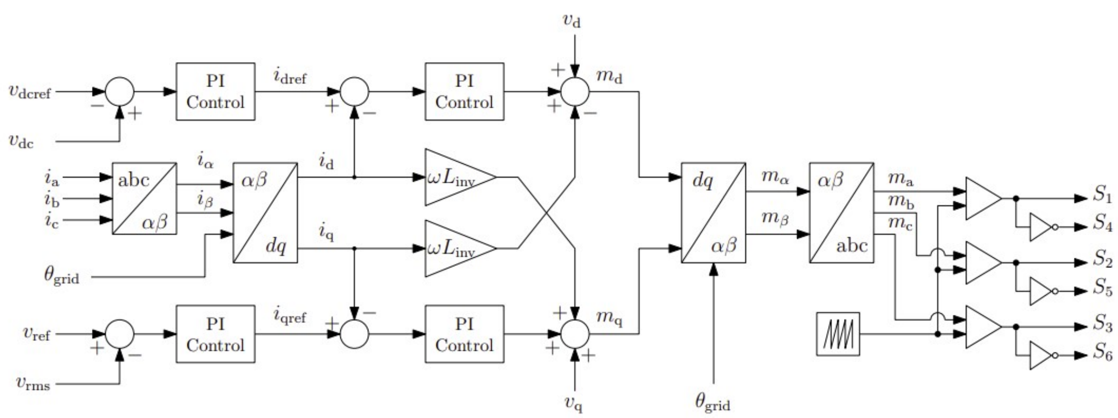


Figure 6.2: DC Fast Charging Inverter Control System[3]

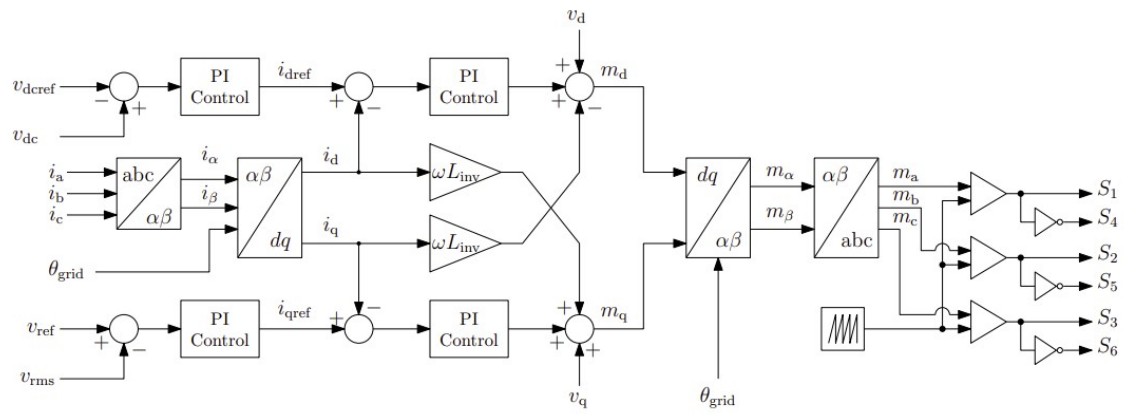


Figure 6.3: DC Fast Charging Battery Charger Control (a) CC Charging (b) CV Charging [3]

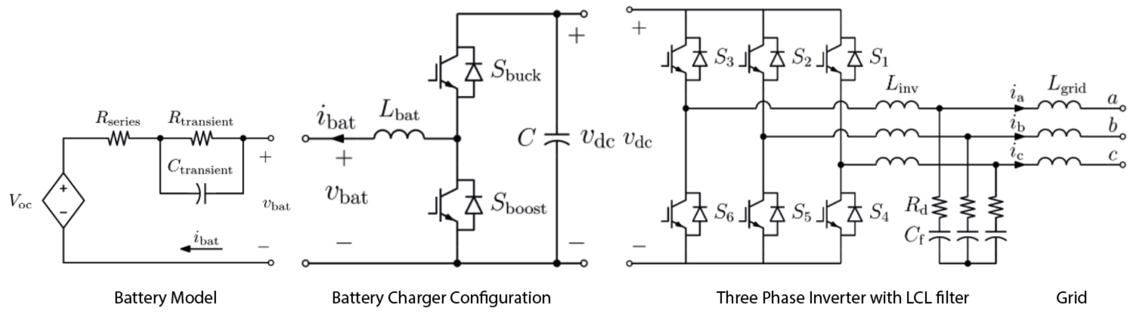


Figure 6.4: DC Fast Charging Electric Circuit Configuration [3]

6.1.2 Simulink Modelling

Moving on to the Simulink model, it is based on the electric circuit configuration mentioned in figure 6.4 using Matlab/Simulink *SimPowerSystem*. The table **??** provides the necesssary data for the model working and simulations.

Parameters	Values
Minimum Modulation Index (m_{min})	0.125
Battery Minimum Voltage ($V_{bat_{min}}$)	$200V$
DC Bus Nominal Voltage (v_{dc})	$1600V$
Simulation Time Step (τ_s)	$2x10^{-6}$
Battery Reference Voltage ($V_{bat_{ref}}$)	$415V$
Battery Reference Current ($I_{bat_{ref}}$)	$200A$
DC Reference Voltage ($V_{dc_{ref}}$)	$1500V$
Power Factor (cos_{ϕ})	0.95
No. of charging slots	10
Maximum Power Rate of EV ($P_{EV_{max}}$)	$90kW$
Overload Factor (k_{load})	1.1
Charging Station Rated Capacity (S_{rated})	$1042kVAr$
Period of AC Voltage Waveform (T)	$1/50s$
DC Power Range of Change (Δr)	10%
DC Bus Voltage Range of Change (Δx)	20%
Charging Station DC Voltage (V_{dc})	$1.5x10^3V$
DC Bus Capacitance (C_{dc})	$18x10^{-3}F$
Battery Open Circuit Voltage (V_{OC})	$400V$
Battery Series Resistance (R_{series})	0.0174Ω
Battery Transient Resistance ($R_{transient}$)	$8100x10^{-3}\Omega$
Nominal Capacity of Battery (C_{nom})	$35x10^3Wh$
Rated Capacity of Battery (C_{rated})	$87.5Ah$
Initial SOC (SOC_{in})	50%
Battery Inductance (L_{bat})	$2x10^{-3}H$
Phase-to-Phase Grid Voltage (V_{grid})	$20x10^3V$
Grid Voltage Fundamental Frequency (f_{grid})	$50Hz$
Ripple Attenuation Factor (RAF)	0.2
Switching Frequency (f_{SW})	$5kHz$
Grid side Inductance (L_{grid})	$0.69x10^{-3}H$
Inverter side Inductance (L_{inv})	$0.48x10^{-3}H$
Damping Resistance (R_d)	1.31Ω
Short Circuit Level (SCL)	$1200x10^6VA$
X/R Ratio	8
Winding 1 Δ Ph-Ph Voltage (V_1)	$20x10^3$
Winding 2 Y_g Ph-Ph Voltage (V_2)	$0.8x10^3$

Table 6.1: Charging Station Parameters according to [3]

Figure 6.5 shows the overall structure of the simple model, with one EV Battery connected to the DC Bus with off-board configuration that is further connected to the inverter which is a *universal bridge* which further connects to the LCL filter and moving on its connection to the transformer that is a *three-phase two winding transformer* finally connected to the grid i.e., *three-phase source*. Figure 6.6 presents low level controller as explained in the theoretical part in subsection 6.1.1 which governs the functioning of the inverter, while figure 6.7 is high level controller that governs the functioning of the IGBT Switches in the DC Bus Battery Charger depending on the SOC i.e., boost or buck charging process.

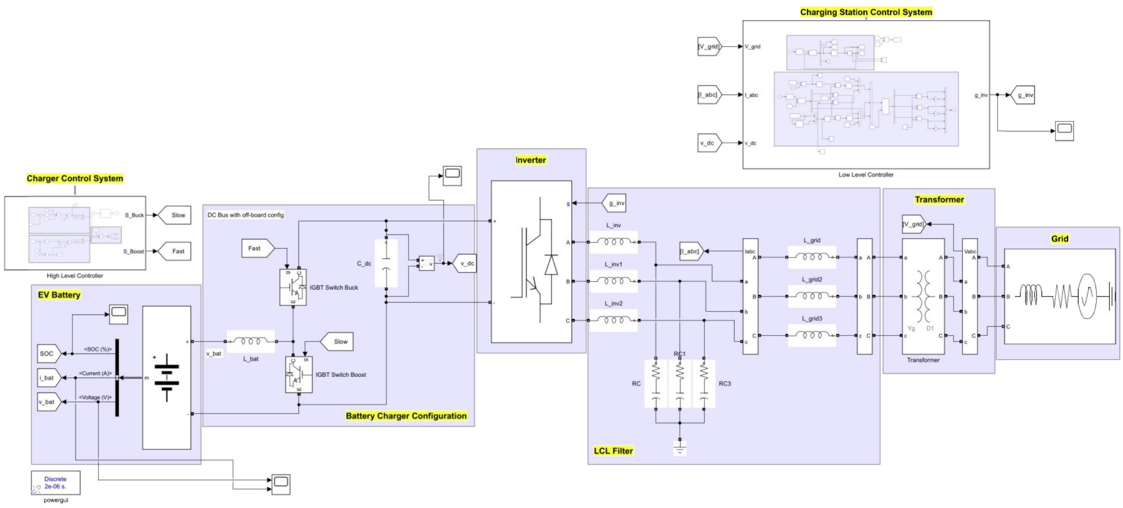


Figure 6.5: DC Fast Charging Simulink Model

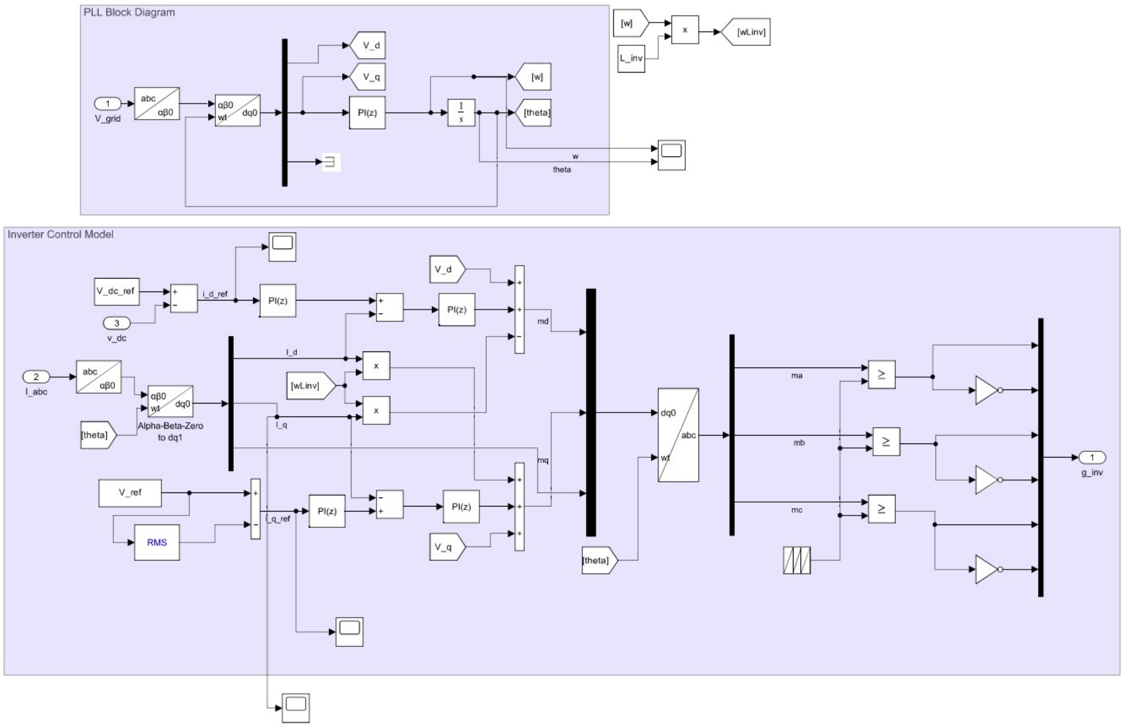


Figure 6.6: Low Level Controller (Charging Station Control System) Simulink Model

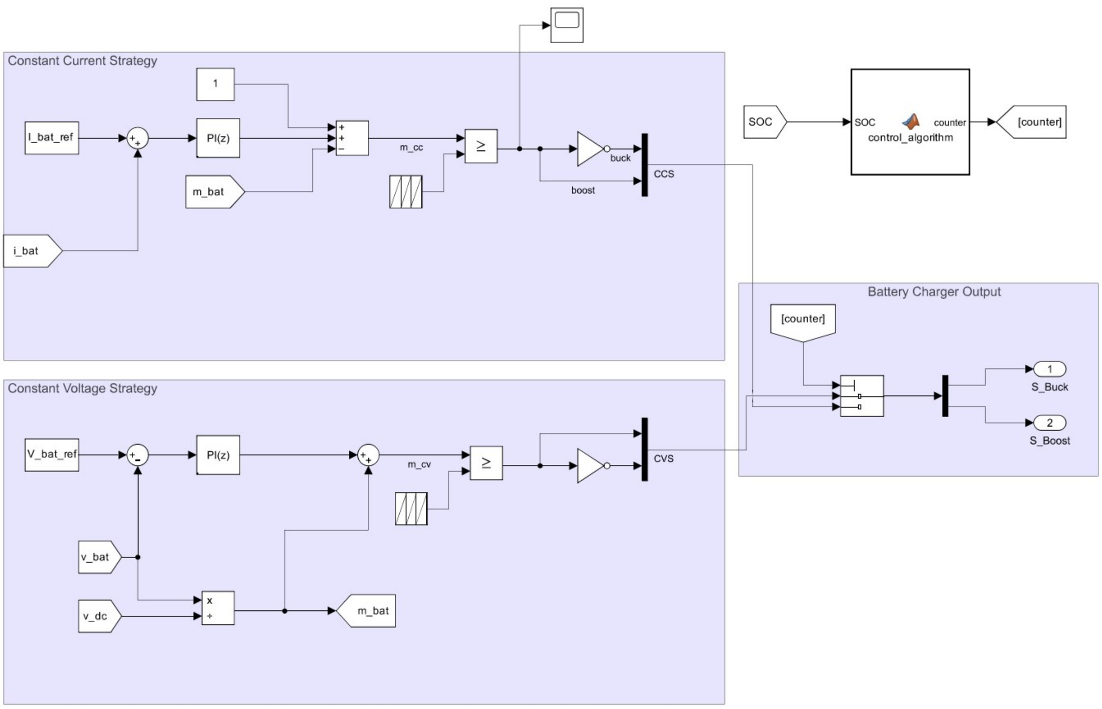


Figure 6.7: High Level Controller (Charger Control System) Simulink Model

6.2 High Voltage Battery Modelling

6.2.1 Battery Specification

The basic idea is to create a High Voltage Battery by using Simulink/Simscape, and within the application, battery modules are present that are *table based* and it comes with a selection of battery module options with different parameters. For the purpose of high voltage battery used for EV traction purpose, ***Valence U27-36XP*** is used and the specifications of the modules are taken from the data-sheet provided by Lithium Battery Inc. as per [39]. The following table 6.2 provides the electrical specifications of the module.

Nominal Voltage	38.4 V
Capacity at 25 Celsius	50 Ah
Energy	1.92 kWh
Discharge Continuous - Peak Current	100 A - 150 A
Discharge Cut-off Voltage	30 V
Recommended Charge Voltage	43.8 V
Recommended Charge CCCV	$\leq$ 25 A - 43.8 V
Specific Energy	102 Wh/kg

Table 6.2: Battery Module Electrical Specifications

By using this specific module, battery pack is created, taking into consideration that connection in series the modules, the voltage increases while connecting parallel, the battery pack capacity is increased. For this case, the modules are connected first in series of 11 modules and then connected together in parallel of 2, hence forming a 2P11S battery pack. The characteristics of the battery pack is given below in table 6.3

Nominal Voltage	422.4 V
Open Circuit Voltage	430 V
Nominal Capacity	100 Ahr
Total weight	412 kg
Maximum Constant Current	50 A

Table 6.3: Battery Pack Specifications

6.2.2 Battery Simulink Modelling

After all the calculations and considerations, simulink model can be created with the specifications mentioned above also keeping in mind the thermal conditions. Figure 6.8 shows the 2P11S configuration of the battery with *voltage sensor* and *current source* used for charging and discharging purposes, while the orange signals are connected all together further attached to one controlled temperature source through *convective heat transfer*. While SoC is calculated by considering the mean of the 22 modules connected together without any further complexities.

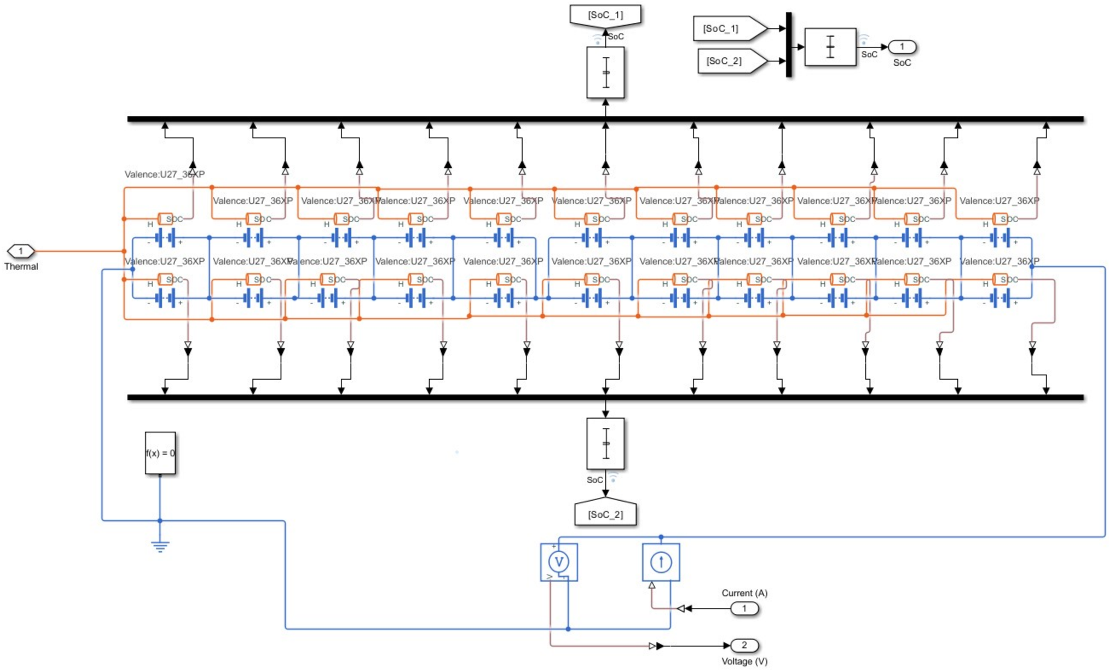


Figure 6.8: Battery Pack Simulink Model

6.2.3 Battery Testing

In this section, discussions are made regarding the testing and the correct working of the battery pack, hence two testing procedures were done, one is ***CCCV Charging and Discharging*** while second is the ***SoC estimation*** by using a Kalman Filter.

CCCV - Simulink

Matlab/Simulink provides *Battery CC-CV* block that implements battery charging procedure i.e., constant current and constant voltage, while for discharging the block uses constant current provided by the input. The following figure 6.9 depicts the modelling implemented [61]. And in figure 6.10 indicates the results i.e., Voltage, Current, Temperature, and SoC timeplots.

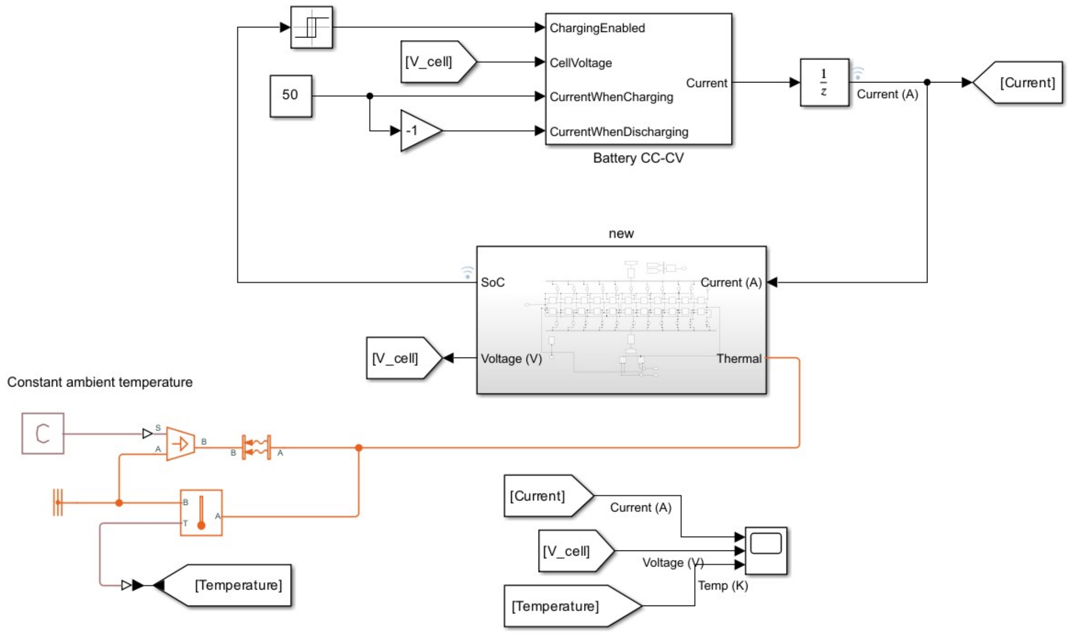


Figure 6.9: Battery Pack CCCV Charging and Discharge Simulink Model

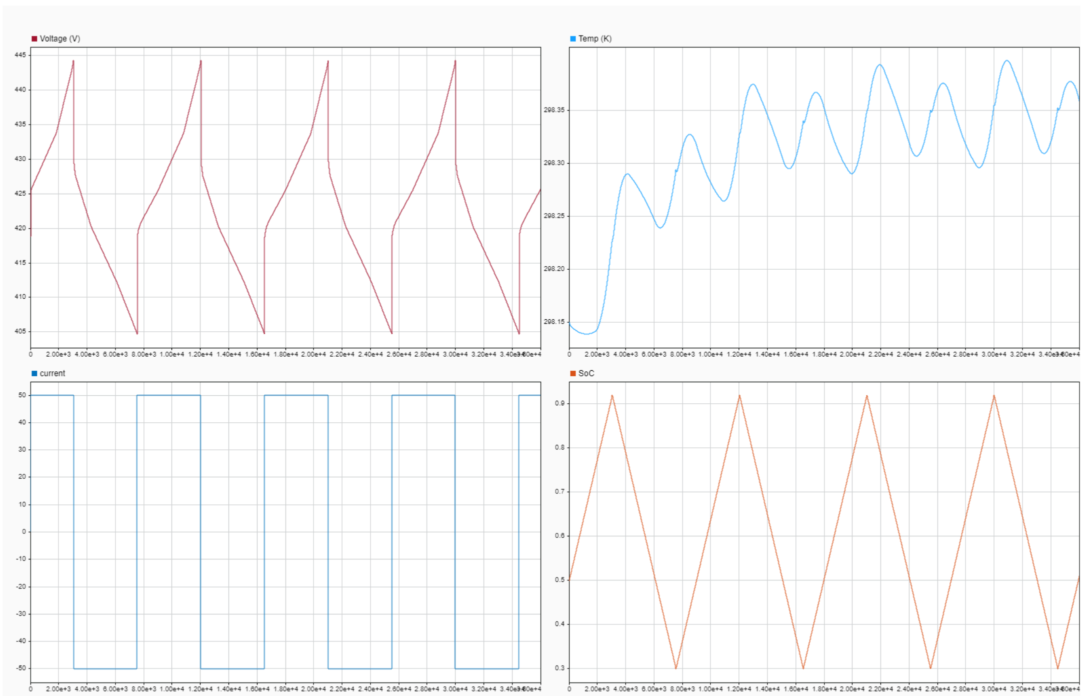


Figure 6.10: Battery Pack CCCV Charging and Discharge Simulation Results

SoC Estimation - Simulink

Moving on to the second testing i.e., SoC estimation, it is performed by using the *SoC Estimator (Kalman Filter)* block, which estimates the SoC using the Kalman Filter constants, it has SoC and polarized voltage as the internal estimator states, while the current is the controlling input, and the cell voltage is the measurement, as depicted in figure 6.11, while figure 6.12 depicts the estimated SoC by the Kalman Filter and the actual SoC driven by the signal from the battery pack.

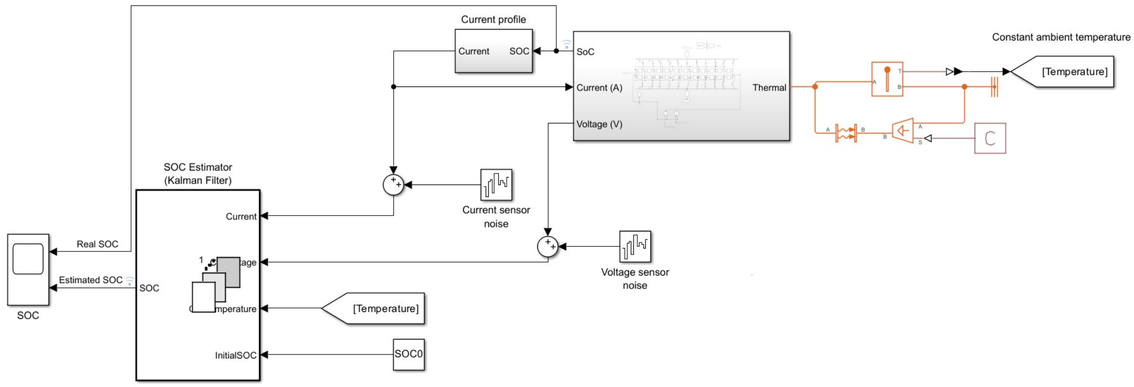


Figure 6.11: Battery Pack SoC Estimation Simulink Model

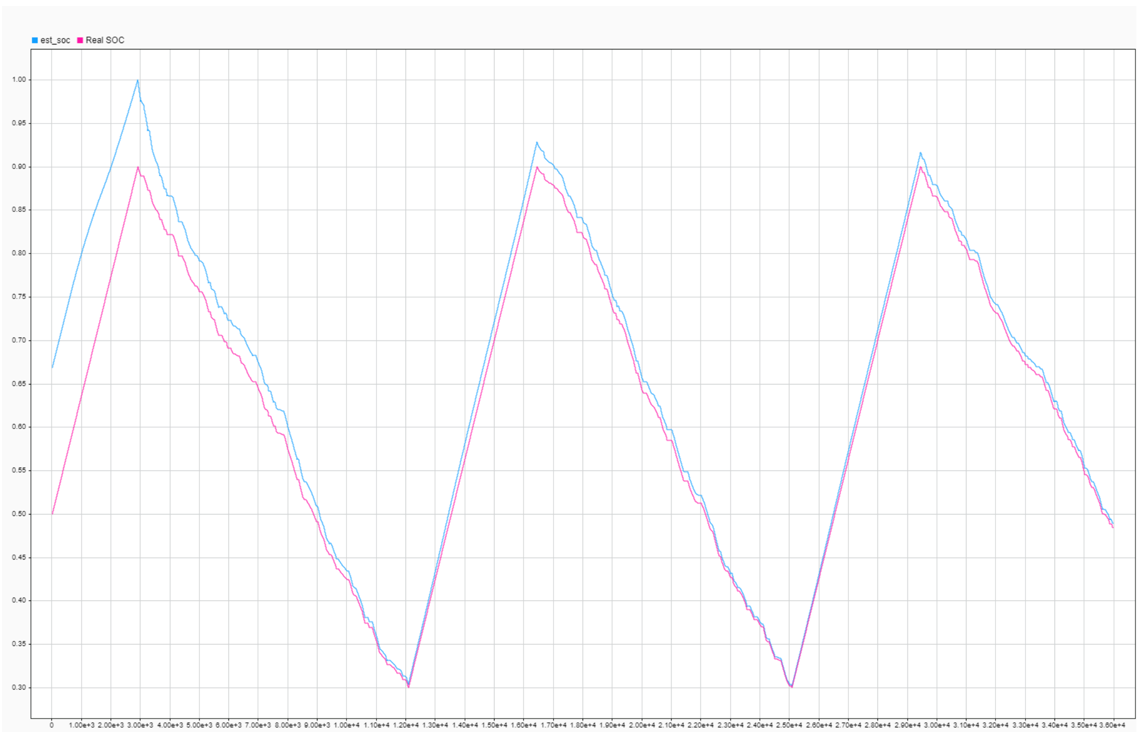


Figure 6.12: Battery Pack SoC Estimation Simulation Results

6.3 Integration of HV Battery with Simple DC Fast Charging Model

The simple model created in subsection 6.1.2 and high voltage EV battery created in subsection 6.2.2 are integrated together with further specific detailing of charging process discussed in this section [60].

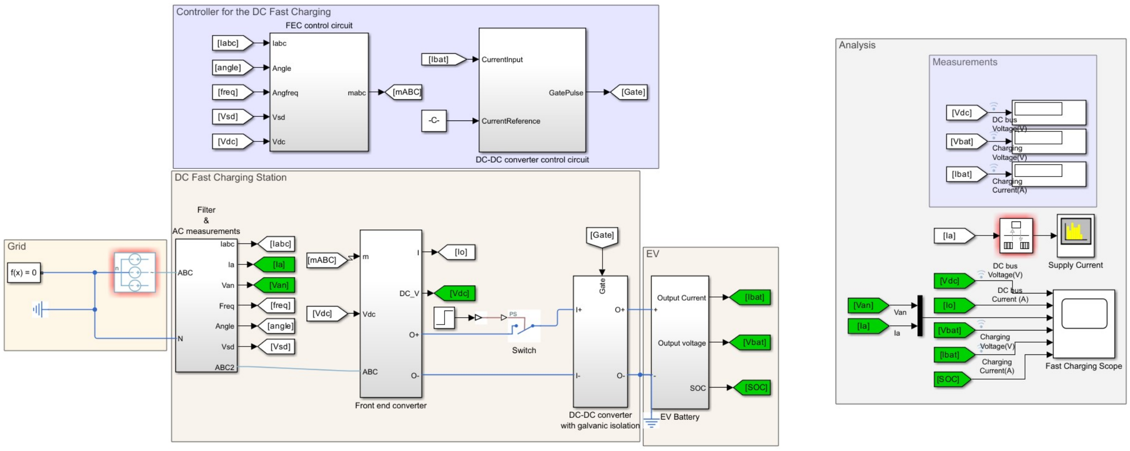


Figure 6.13: DC Fast Charging Station with High Voltage Battery Integration

The figure 6.13 shows the overall simulink model, which consists of HV Battery pack charged by the grid through the DC fast charging station, as can be seen, it is composed of multiple stages to convert the AC voltage coming from the grid to DC voltage as per the limitations and specifications of the EV battery. In the following the model is discussed with its working principle.

6.3.1 Grid

It is a *constant voltage three phase source* i.e., constant voltage amplitude and frequency supply to the DC charging station, it main role is to provide power as an input to the charging station

6.3.2 DC Fast Charging Station

As depicted in the figure 6.13, this section consist of three different subsystems.

Filter and AC Measurements

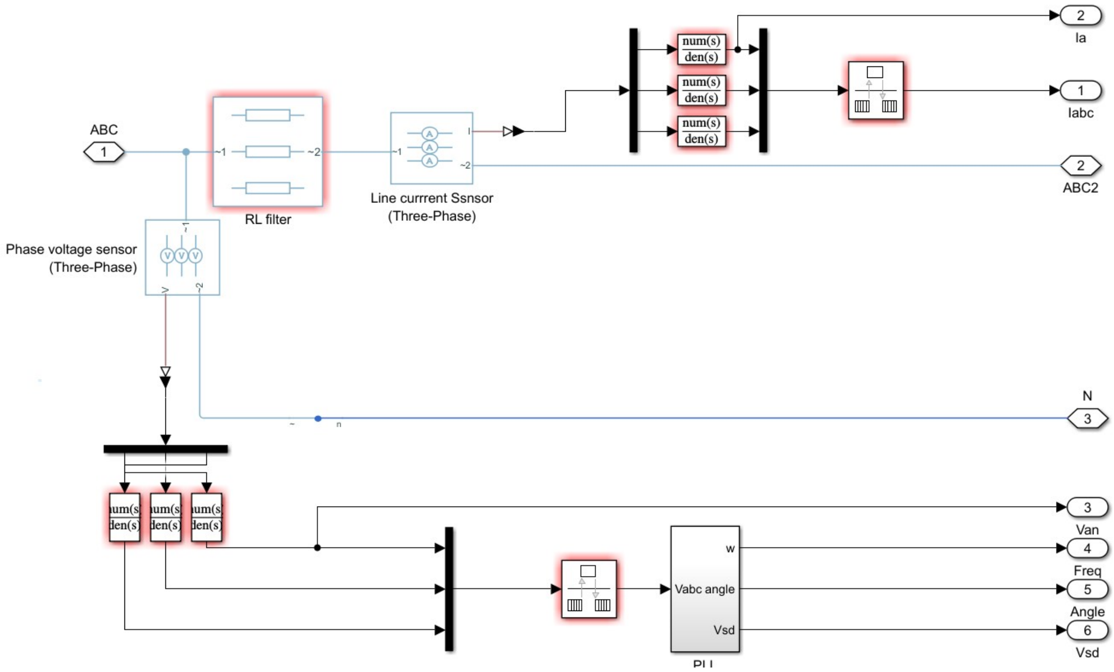


Figure 6.14: Filter and AC Measurements

Figure 6.14 shows the components of this subsystem, which is designed to filter the harmonics from the line current beneficial for the power quality, while the current and voltage sensors are used to fetch real-time based data for better controlling and monitoring of the process, and the data then can be used by the controllers for operation purposes.

Unity Power Factor (UPF) Front End Converter (FEC)

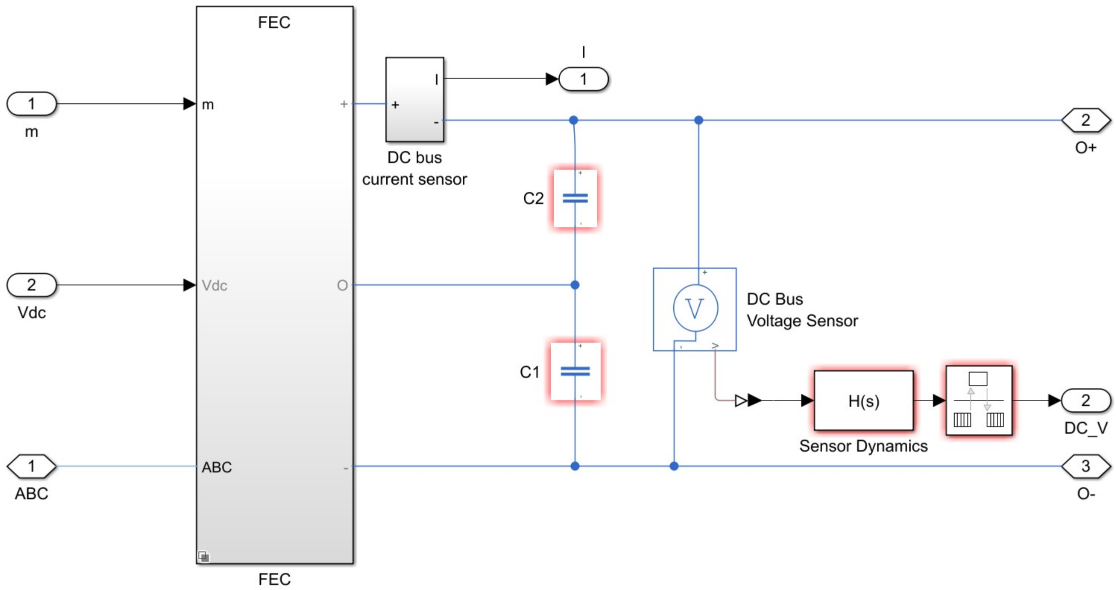


Figure 6.15: Front End Converter

As the name of the subsystem suggests, it converts AC to DC with three degree of fidelity, i.e., Average, Two-Level, and Three-Level. The main function of the FEC is to manage the DC output voltage and to make sure of the unity power factor, such to lower the reactive power in order to improve efficiency by adjusting the input current amplitude and phase in order to make it similar to that of the grid voltage hence obtaining unity power factor. And also the DC output voltage is regulated by the FEC by modulating the switching devices.

DC/DC Converter (Galvanically Isolated)

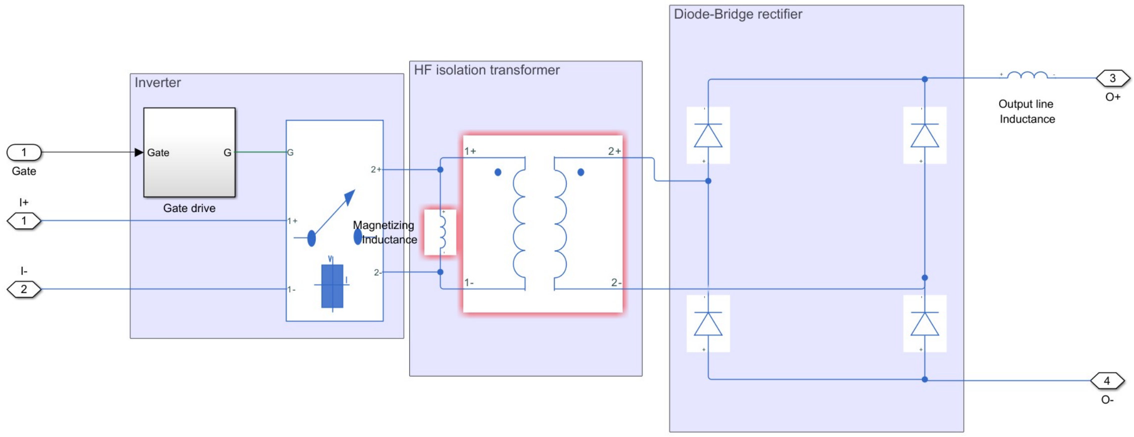


Figure 6.16: DC/DC Converter (Galvanically Isolated)

As the figure 6.16 depicts, it consists of three components, i.e., Inverter initiates high frequency AC voltage, High frequency isolation transformer that provides galvanic isolation, improving safety, and able to step-down or step-up the voltage adjusting the voltage level, Diode-Bridge rectifier, that converts back the AC to stabilized DC voltage used for charging. The main function of the DC/DC converter subsystem is to provide the EV battery with constant charging current, while also giving isolation safety between the grid and the EV.

High Voltage EV Battery

The EV Battery introduced and the model created in section 6.2 and figure 6.8 is integrated into this model of DC fast charging, with the generic idea of the ESS of the EV is to store the energy transferred by the grid through the DC charging station with precise voltage and current control during the charging phase, then utilized by the EV for traction and powering the auxiliary components during the discharging phase.

6.3.3 Circuit Controllers

FEC Control Circuit

It takes the current, phase amplitude and frequency and velocity from the filter and AC measurement block and a DC voltage from the FEC block as feedback to manage the operation of the FEC, making sure that the input AC is transformed into stabilized DC voltage and also it controls so that the unity power is maintained done by dynamically altering the switching patterns as done in the simple charging station LLC.

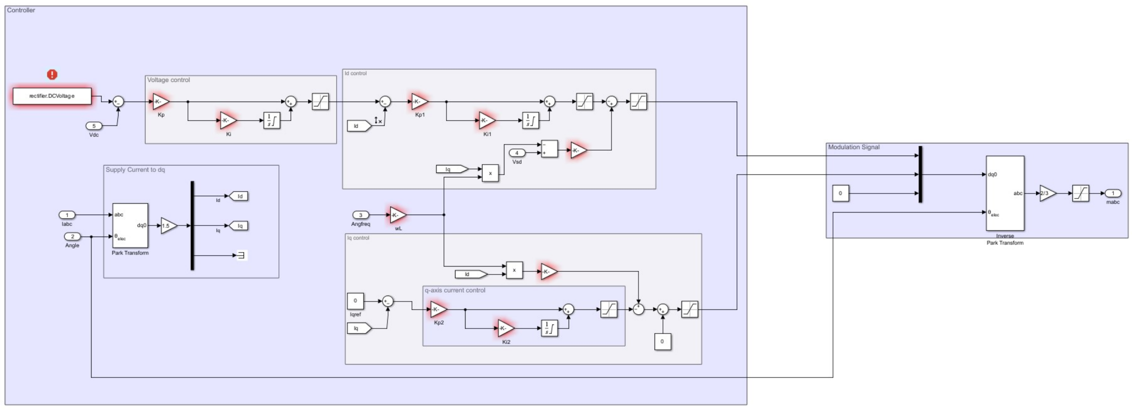


Figure 6.17: FEC Control Circuit

DC/DC Converter Control Circuit

It has a function of maintaining the charging current to be less fluctuating or close to constant. It changes the DC/DC Converter operation depending on the feedback coming from the EV battery current sensor along with the current reference fed into the control circuit and output is a gate pulse that is fed back to the DC/DC converter.

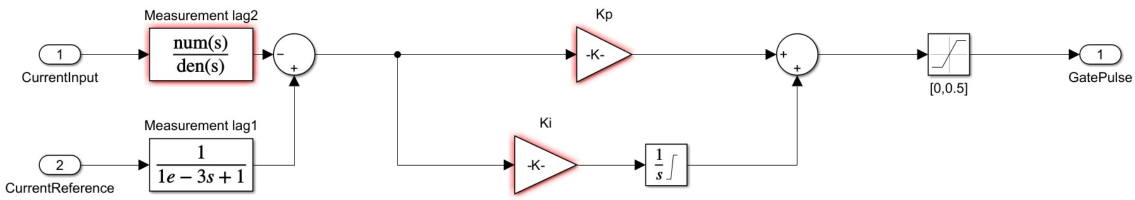


Figure 6.18: DC/DC Converter Control Circuit

6.3.4 Charging Process

1. Three-phase AC supply is provided by the grid to the charging station.
2. High frequency harmonics are then eliminated from the current by the RL filter.
3. The voltage and current sensors measured the filtered AC supply.

4. Then going through the FEC, the AC supply is then converted into a stable DC supply while maintaining the unity power.
5. The DC voltage is then reversed to high frequency AC by the inverter, allowing for efficient transformer design.
6. Then the HF AC goes through the isolation transformer, altering the voltage as required by the EV battery.
7. By using the diode-bridge rectifier, the HF AC is rectified back to the DC.
8. DC/DC converter regulates the output so to provide a stable and efficient supply of constant current.
9. Finally, the HV battery is then charged with the regulated DC current, ensuring safe and efficient storing of the energy.

The final model developed in this chapter illustrates the integration of the HV battery with in a Fast Charging System, the main goal of this is to provide a comprehensive and clear framework that will be further integrated into a more standardized based model, i.e., IEC 61851 based and SAE J1772 based with their respective communication protocols flow states in order to analyze and investigate different scenarios i.e., short circuit testing, load dump, and so on, and finally making a fair comparison between them by using the results obtained.

7 Detailed Model of an European and USA Charging Station

7.1 EU and USA Communication Based Models

Moving to an in-depth analysis of the EV charging. in this section the communicative link between the EV and EVSE through the sensors and coupler is discussed. The two couplers i.e., CCS 1 - SAE J1772 (USA) and CCS 2 (EU). The charging process involves high level digital communication (HLC) between the EV and EVSE subsystems. With the help of mathworks Mathlab [59], the designing of the model was performed and altered depending on the needs of this research. Taking into consideration that some hypothesis were purposed such as this model is without the in depth thermal management. The main idea was to construct the communicative domain that links the communication protocols with the standards respectively in order to mimic the actual corresponding between the EVSE and EV. In the following, detailed description is given for the both EU and USA based fast charging models, while the basic structure of the charging station with the vehicle battery remains the same as portrayed in the figure 7.1 consisting of Electric vehicle with its Battery Management System (BMS) followed by specific standard based charge control and the communication control i.e., high level communication (HLC) that further is connected with the charging sensors and coupler block and then connected to EVSE subsystem which consists of standard based supply equipment communication control and charge control going into the EVSE battery charger. For further investigation of this model, the reference model could be found on [59].

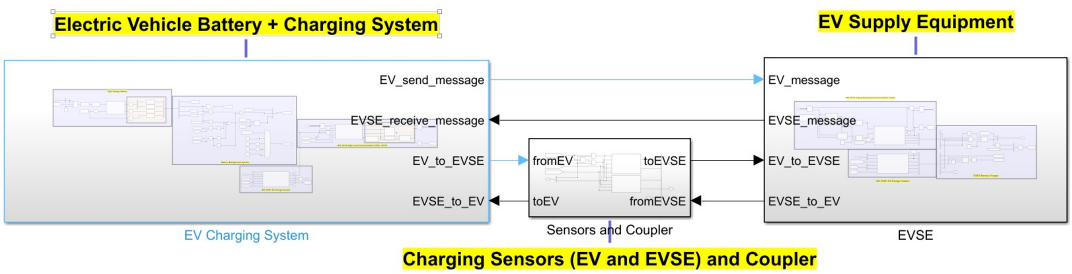


Figure 7.1: Simulink Model of a Communication Based Model

The following section discuss in detail the model subsystems i.e., Electric Vehicle Battery with Charging System, Charging Sensors (EV and EVSE) and Coupler and

EVSE.

EV Battery and Charging System:

As depicted in fig 7.2, depending on the charge control coming from the EV charge control module which will be discussed further in the section with respect to the standard used, the current is communicated to the HV battery from the EVSE through the sensors and coupler, that feeds the current into the Lithium Ion Battery Pack with specific characteristics [59], with a certain delay the output from the HV Battery i.e., Current, SOC, Voltage and Temperature is feed as an input to the BMS, which take care of the following specifications.

1. Check if the SOC is greater or equal to the SOC Target
2. Check if the SOC is greater than a certain threshold for Buck and Boost Charging
3. Check if the Voltage of the battery is lower than the Maximum Voltage of the battery according to its specifications.
4. Check if the Battery Temperature is lower than the Maximum Temperature.
5. And also, check if the EV is OK i.e., ready to be charged or not.

The above checks serves as the conditions that need to be specified which gives the output whether buck or boost charging is performed and if the charging is complete to stop the charging process or not, and if the Vehicle is ready to be charged, these output are then inputted into the EV Communication control and DC Charging Control Module.

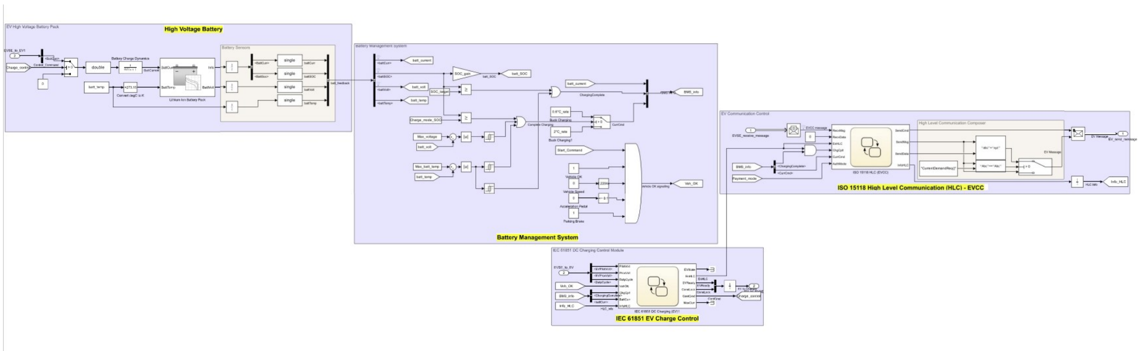


Figure 7.2: EU based EV and Charging System Model

The EV Charge Control Module is developed as a state flow chart that is conditioned according to the specific standard used that takes input as the pilot and proximity pins voltages and duty cycle coming from the EVSE through the sensors, Vehicle OK indication from the BMS and HLC information from EV Communication Control. The state flow then outputs the EV State of Charge according to the standard, HLC enable, EV ready to charge or not, connector lock, charge control that serves as a gate way to charge the battery.

Finally, the EV communication control area consists of standard based EV HLC communication control state flow chart that takes as an input the message coming from the EVSE, either to enable HLC from the EV Charge Control Module, information from the BMS and the payment method i.e., External Identification Means (EIM) or Plug and Charge (PnC). And it outputs the EV message that is to be communicated to the EVSE along with the Data i.e., current to charge the vehicle and HLC Information that is fed into the EV Charge Control as mentioned before.

Sensor and Coupler:

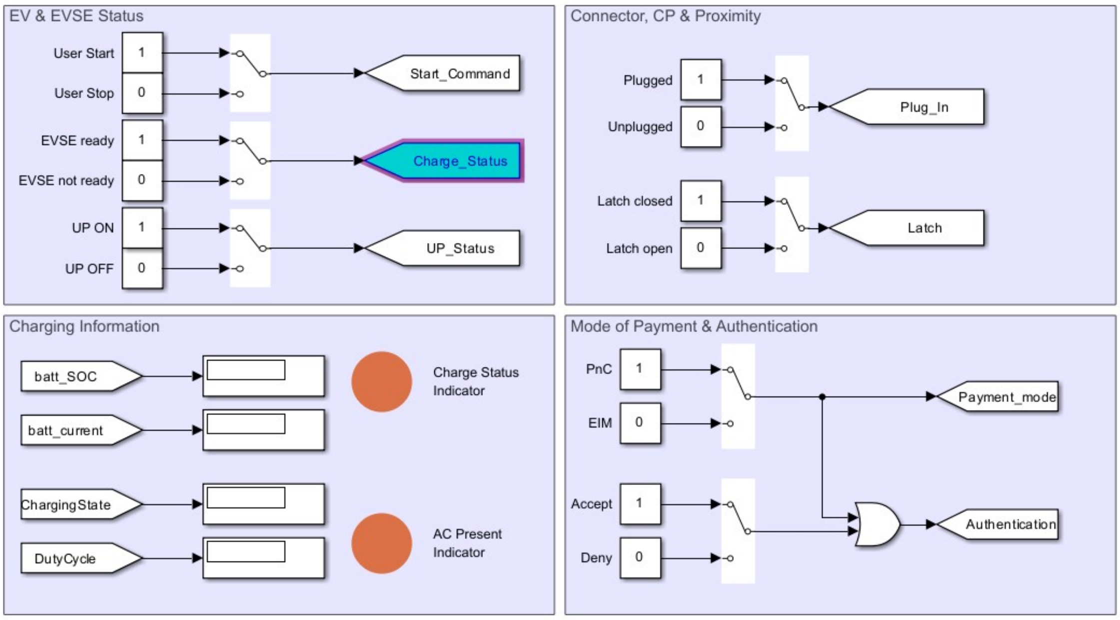


Figure 7.3: User Variable Switches for different conditions of charging

The fig 7.3 indicates the monitoring system used for the DC Fast charging setup. A brief description is given below.

1. **EV and EVSE Status:** This section is used to control the EV and EVSE status.

- User Start/Stop is used to stop and start the charging process that gives the output as start command.
- EVSE Ready indicates if the EVSE is ready for the charging or not giving output as Charge Status.
- UP represents the Utility Power on and off switch, that gives an output of UP Status.

2. **Connector, Control Pilot and Proximity:** This takes control of the connection status and proximity detection and these controls are used by the sensor and coupler block.
   - Plugged/unplugged indicates the plugging of the charging connector into the vehicle.
   - Latch open/closed indicates the mechanical positioning of the latch cover.
3. **Charging Information:** It indicates the charging process information i.e., SOC, battery current, charging state and the Duty cycle of the EVSE.
4. **Mode of Payment and Authentication:** It indicates the method used for payment such as PnC i.e., Plug and Charge and EIM i.e., External Identification Means, which outputs the payment mode fed into the EVSE and Authentication i.e., whether it is accepted or not.

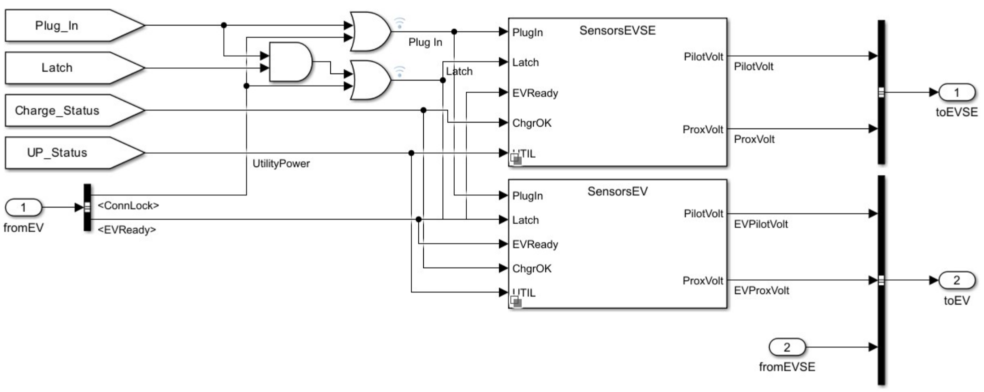


Figure 7.4: Sensor and Coupler

The fig 7.4 indicates the subsystem of the sensor and coupler that consists EVSE Sensors block and EV Sensors block that is a matlab script containing the conditions working as a function of the voltage of different pins i.e., proximity and pilot pins and is also function of plug in, latch, EV ready Utility power and if the EVSE charger is OK or not. It is basically used to build a communication pathway between the EV and EVSE based on voltages. Hence the input to these blocks are Plugin, Latch, EVReady, ChgrOK and UTIL. while the outputs are to the EVSE or to the EV which are in terms of voltages i.e., proximity and pilot voltages. For a deeper view inside the two blocks, [59] could be used to view how the function block works and what are the conditions used to output the results in terms of voltages.

EVSE:

In this subsystem as shown in fig 7.5 there are three areas inter-linked together. Firstly, it consist of Supply Equipment Communication Control (SECC) that takes the message from EV and the current demand data and whether to enable HLC commanded by the EVSE Charge Control and Authentication as mentioned above. and this state flow chart then according to the communicative standard outputs the command, message and data to the EVSE, while the HLC information serves as a feedback to the EVSE charge control and current command, pre-charging, and power command is fed into the EVSE battery charger that further goes to the sensors.

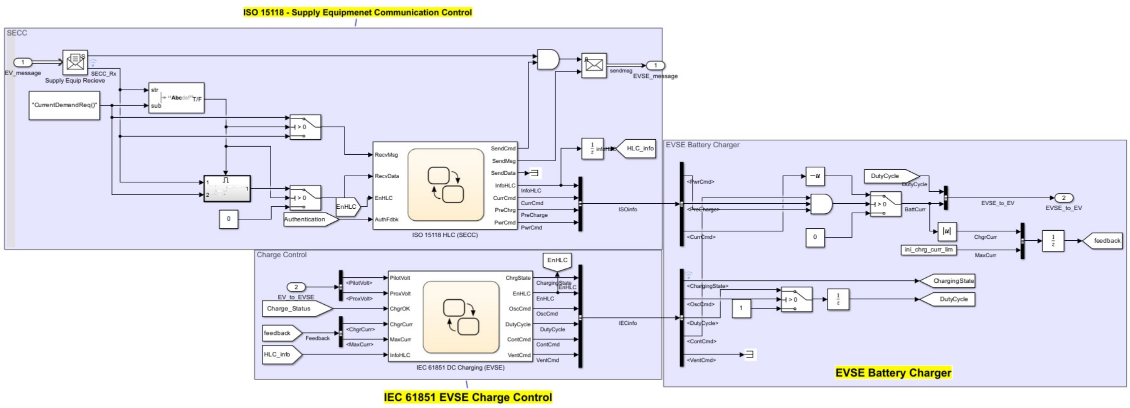


Figure 7.5: EVSE Model

Considering the EVSE Charge Control, it varies depending on the standard used as mentioned before, and it takes the output of the sensors i.e., PilotVolt and ProxVolt, Charge Status, and feedback from the EVSE charger and HLC information from the SECC and outputs the state of charge of the EVSE, whether to enable HLC or not, Oscillation command onto which the duty cycle depends, either to stop charging or not (ContCmd) and VentCmd.

The structure of the model described up till now is the same for both EU and USA based charging, while the main difference lies in the communication protocol used and the Charge control standards for both EV and EVSE used for respective regions, discussed in the following sections i.e., 7.1.1 and 7.1.2.

7.1.1 EU Standard State Flow

IEC 61851 DC Charging

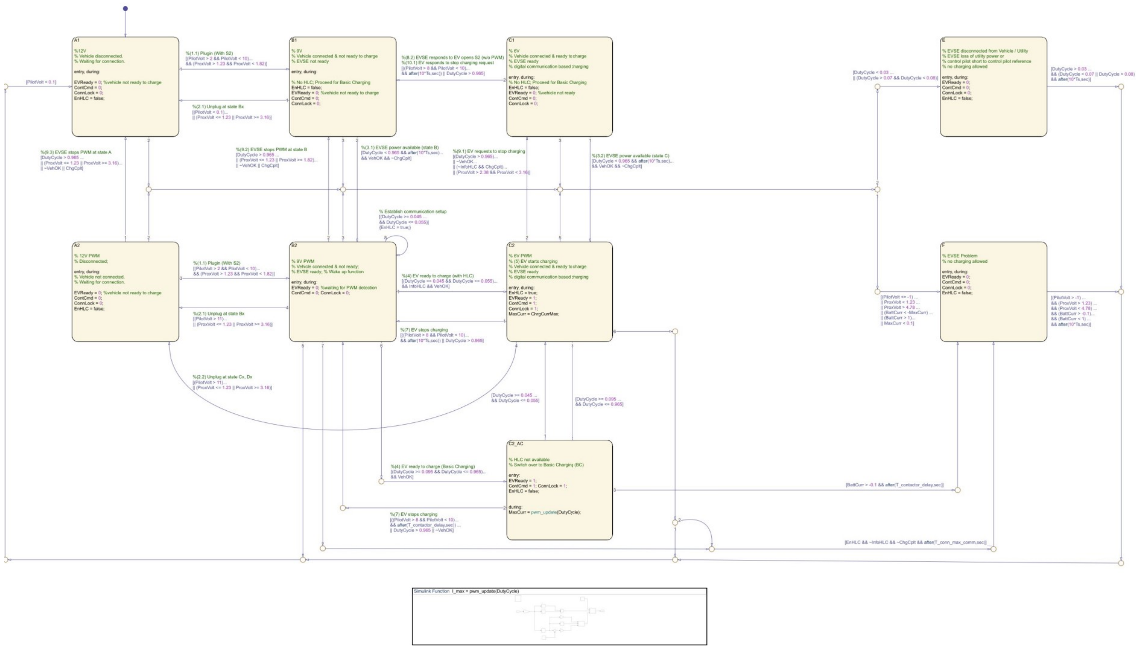


Figure 7.6: IEC 61851 DC Charging EV State Flow

The fig 7.6 indicates the state flow chart of the EV States throughout the Charging Process, this chart was developed under the standard IEC 61851-1:2017 [27, 59] and it works on the conditions i.e., inputs into the state flow chart, the table 7.1 shows a better brief analysis of each state.

IEC 61851-1:2017, States detected by the EV	
A1	Vehicle not connected, waiting for connection
A2	12V PWM, Vehicle not connected
B1	9V, Vehicle connected but not ready, EVSE not ready
B2	9V, Vehicle connected but not ready, EVSE ready
C1	6V. Vehicle connected and ready to charge, EVSE ready, Digital Communication
C2	6V, EV charging with HLC
C2 AC	HLC disabled, Basic Charging
E	EVSE disconnected from EV or Utility
F	EVSE related problem, charging not allowed

All of these states are controlled by the Pilot, Proximity Voltages, Battery Current, Duty Cycle

Table 7.1: States detected by the EV according to the IEC 61851-1:2017

Similar concepts apply when the states detection is done by EVSE State flow in figure 7.7, described in table 7.2

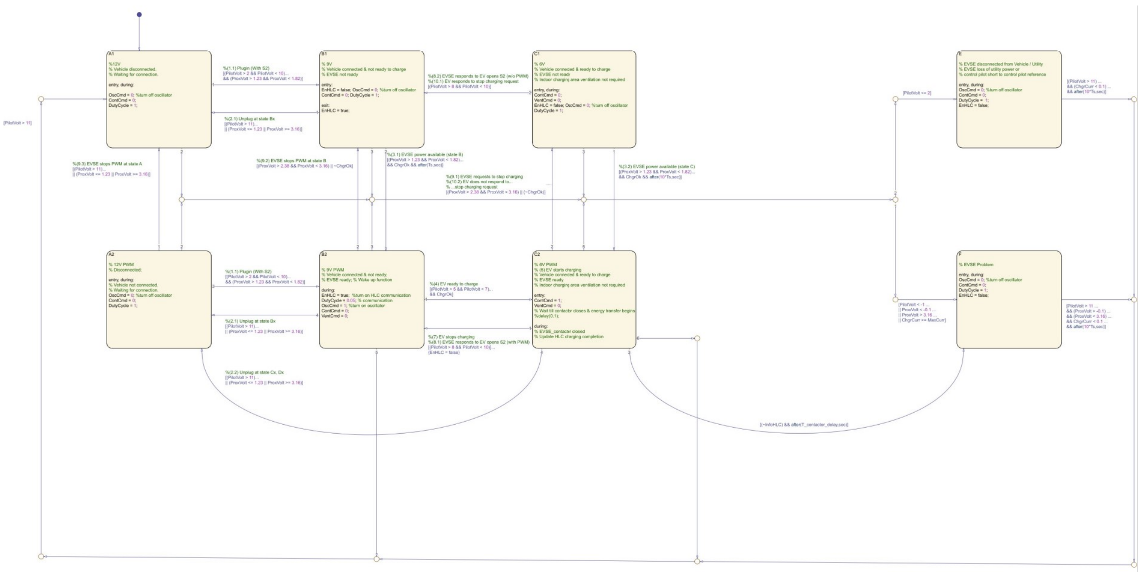


Figure 7.7: IEC 61851 DC Charging EVSE State Flow

IEC 61851-1:2017, States detected by the EVSE	
A1	Vehicle not connected, waiting for connection, oscillator off
A2	12V PWM, Vehicle not connected, oscillator off
B1	9V, Vehicle connected but not ready, EVSE not ready
B2	9V, Vehicle connected but not ready, EVSE ready (Wake up function), HLC enabled, oscillator on
C1	6V. Vehicle connected and ready to charge, EVSE not ready, oscillator off
C2	6V, EV charging with HLC, EVSE waits till the contactors closed before energy transfer
E	EVSE disconnected from EV or Utility, EVSE loss of utility power, control pilot short to control pilot reference, oscillator off
F	EVSE related problem, charging not allowed

All of these states are controlled by the Pilot, Proximity Voltages, Battery Current, Duty Cycle

Table 7.2: States detected by the EVSE according to the IEC 61851-1:2017

ISO 15118 Communication Protocol

As described at the start of this chapter, the basic idea is to develop the charging of high voltage battery based on communication between the EV and EVSE. In EU, the communication standard used is ISO 15118 respectively for the EV and EVSE [32].

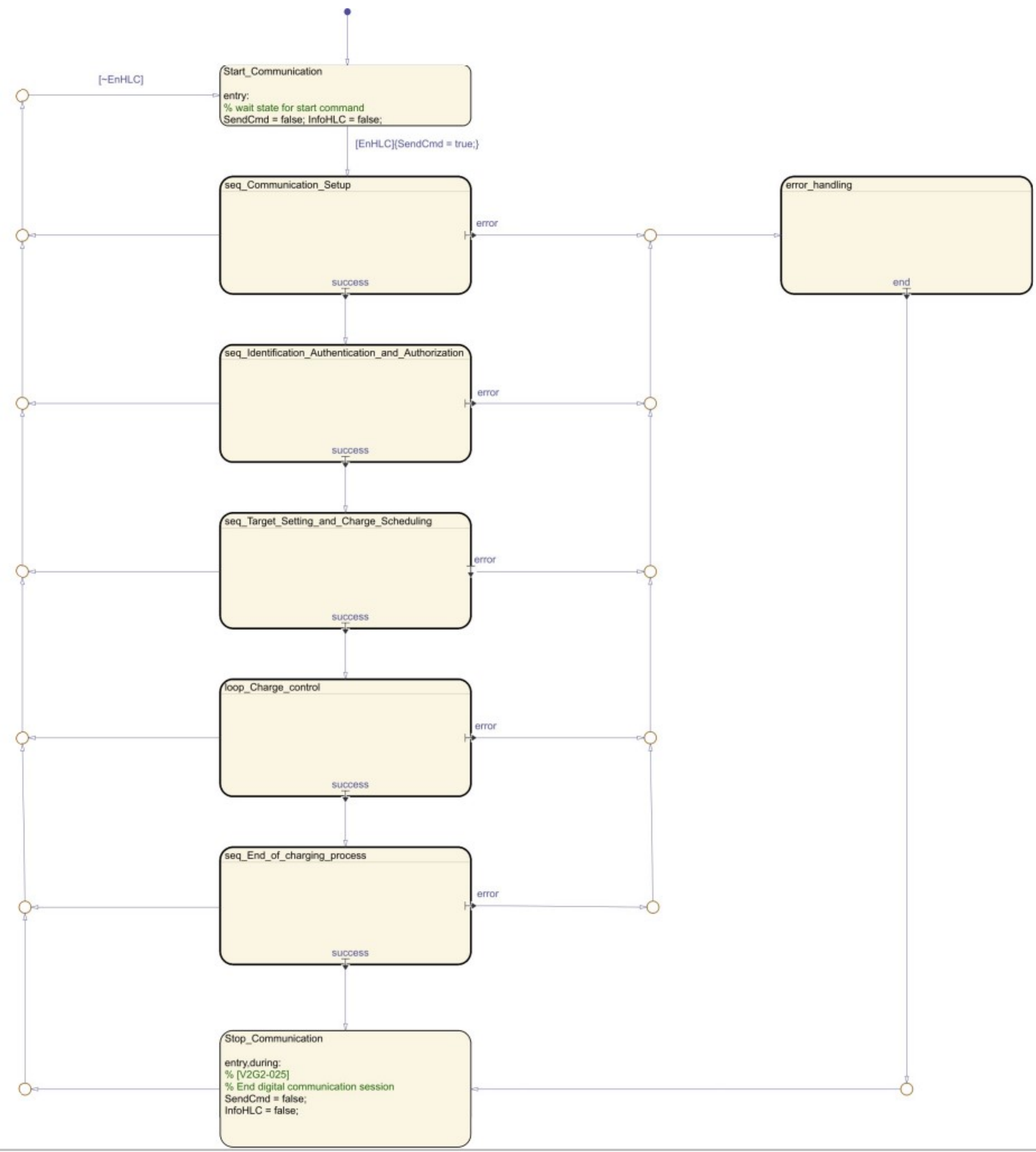


Figure 7.8: ISO 15118 Communication State Flow

The flow chart represented in figure 7.8 works in hand with the charge control IEC based standard. The following table explains better how the EVCC and SECC works coherently together to establish communication during charging.

ISO 15118, Communication Protocol - EVCC and SECC	
Start_Communication	Waiting for communication to start, no communication between EV and EVSE
Seq_Communication_Setup	Initialize communication session, Transport Layer Security (TLS) establish, Setup session start
seq_Identification_Authentication_and_Authorization	Checking of available services, authentication and authorization performed
seq_Target_Setting_and_Charge_Scheduling	EV charging parameters discovery and communication with EVSE, Checking of cable in loop, initialization of Pre-Charge
loop_Charge_control	Power transfer enabled, loop charging and rescheduling performed, power delivery turned off if charged completed
seq_End_of_charging_process	Welding detection performed, metering receipt and session stop
Stop_Communication	End of digital communication session
error_handling	If either the EV or EVSE are unable to send or receive message or data then after a certain timeout depending on the stage of the flow chart i.e., after timeout, it proceeds to the error handling block where the session would be stopped if required with the "error()" message

Table 7.3: ISO 15118 Communication sequence between the EV and EVSE [32]

7.1.2 USA Standard State Flow

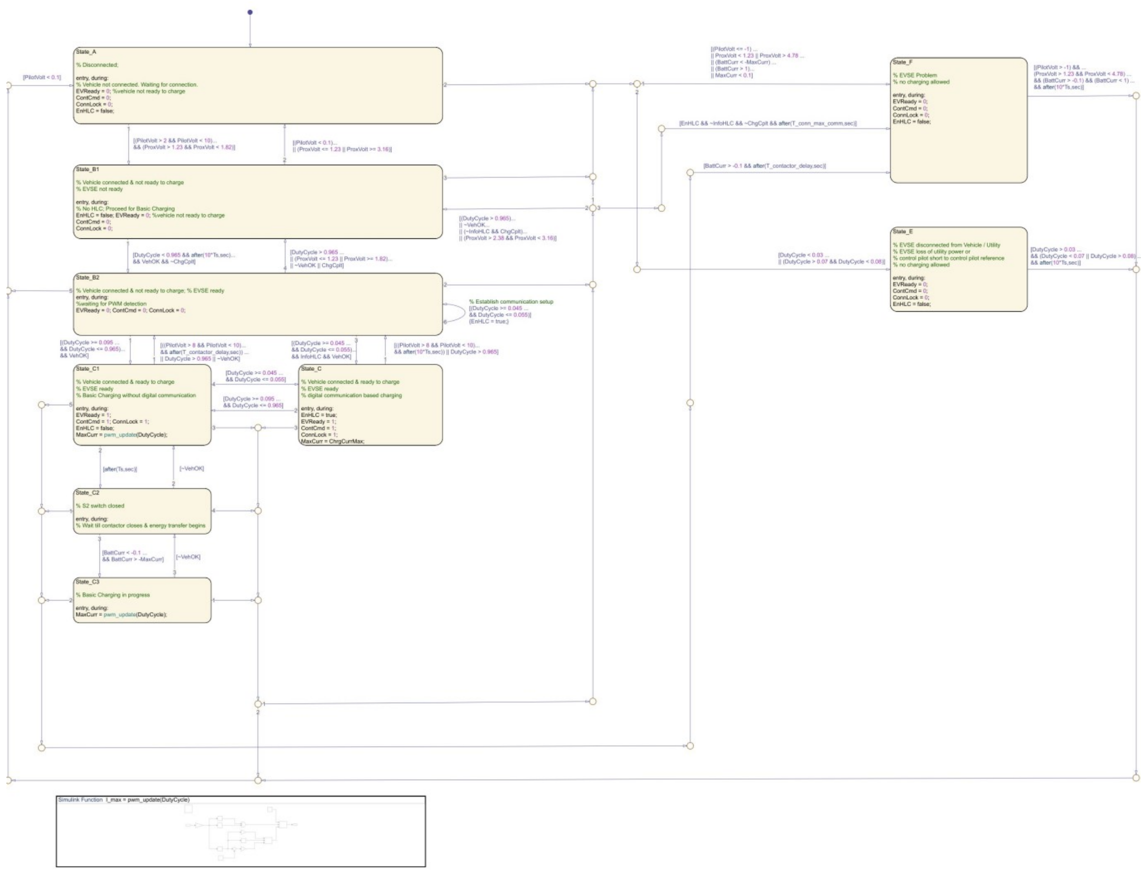


Figure 7.9: SAE J1772 DC Charging EV State Flow

In figure 7.9, the flow chart for the EV Charge Control according to the SAE J1772 standard [29] is given and in table 7.4 the functioning of each state is defined accordingly.

SAE J1772, States detected by the EV	
A	Vehicle disconnected, waiting for connection
B1	Vehicle connected but not ready to charge, EVSE not ready, HLC disable
B2	Vehicle connected but not ready to charge, EVSE ready, PWM detection
C1	Vehicle connected and ready to charge, EVSE ready, Basic charging without HLC
C	Vehicle connected and ready to charge, EVSE ready, HLC enabled
C2	S2 Switch closing, waiting for the contactor to close and begin charging
C	Charging in progress
E	EVSE disconnected from EV or Utility, UP loss, no charging allowed
F	EVSE problem, charging not allowed

Table 7.4: States detected by the EV according to the SAE J1772:2024 [29]

Similar procedure follows for the flow chart of the EVSE, as given in table 7.5 and depicted in the simulink state flow in figure 7.10.

SAE J1772, States detected by the EVSE	
A	Disconnected, waiting for EV connection, Oscillator OFF
B1	Vehicle connected but not ready to charge, EVSE not ready, Oscillator OFF
B2	Vehicle connected but not ready to charge, HLC enabled, Oscillator ON
C1	Vehicle connected and ready to charge, EVSE ready
C2	EVSE contactor closed
C3	Charging in progress
D1	Vehicle connected and ready, indoor ventilation required, EVSE not ready and ventilation unsupported
E	EVSE disconnected from EV or Utility, UP loss, no charging allowed, Oscillator OFF
F	EVSE problem, charging not allowed

Table 7.5: States detected by the EVSE according to the SAE J1772:2024

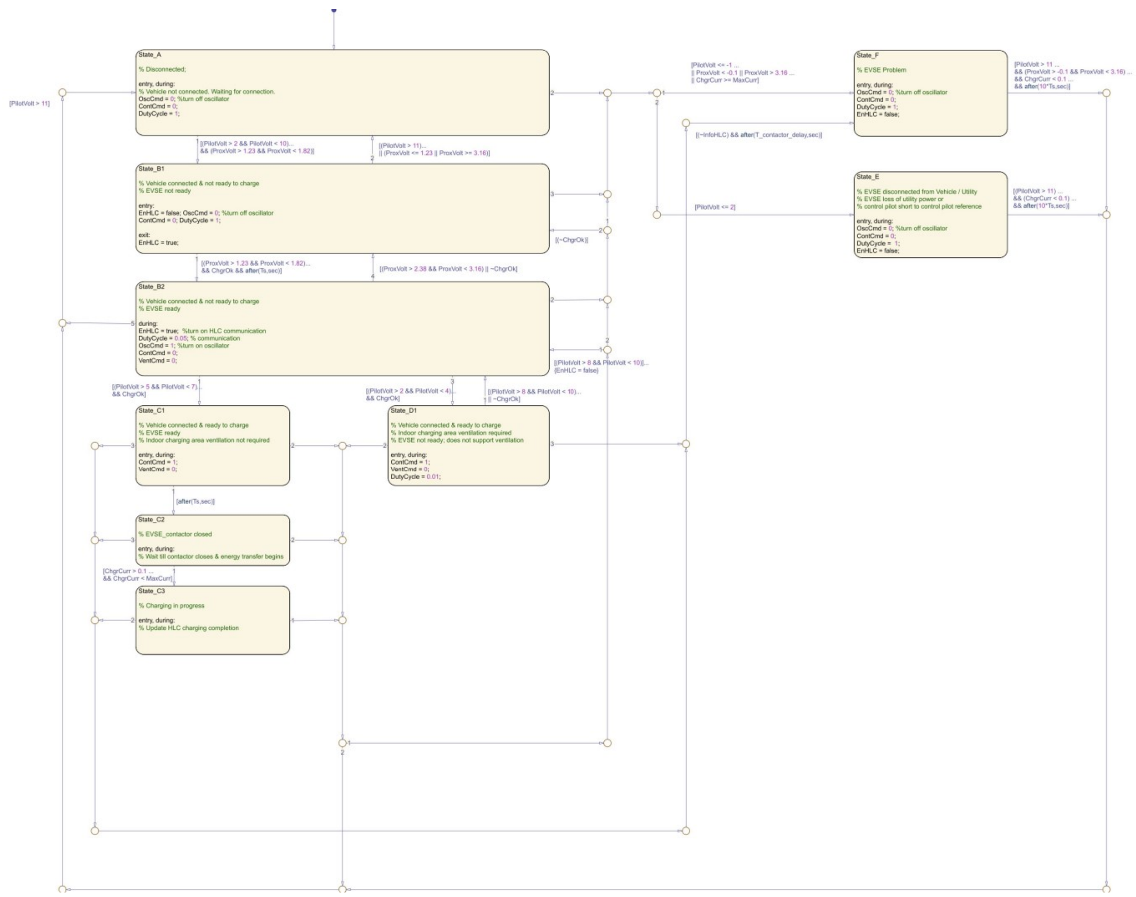


Figure 7.10: SAE J1772 DC Charging EVSE State Flow

DIN SPEC 70121 Communication Protocol

According to SAE J1772 APPENDIX F F.1.10.1 [29], there is a flexibility of using either the ISO 15118 or DIN SPEC 70121 communication protocol, for convenience and also a comparison of the communication standards, DIN SPEC is chosen. Figure 7.11 indicates the communication flow and interaction between the EV and EVSE, while table 7.6 states how the protocol functions.

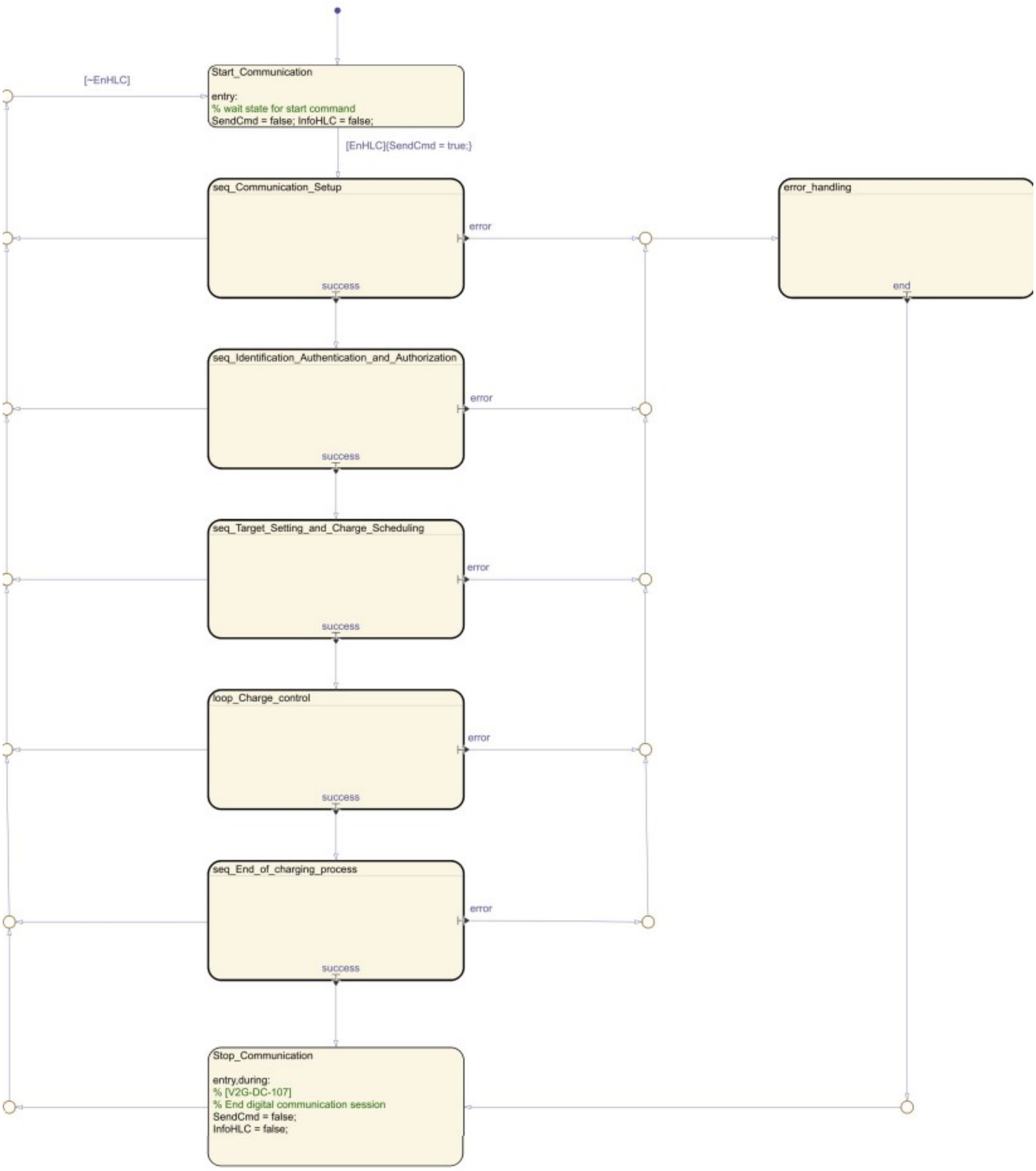


Figure 7.11: DIN SPEC 70121 Communication State Flow

DIN SPEC 70121, Communication Protocol - EVCC and SECC	
Start_Communication	Initiating communication between EV and EVSE
seq_Communication_Setup	Establish communication session, EVSE certificate as TLS server, TLS Session established
seq_Identification_Authentication_and_Authorization	Available services check, check authentication and authorization of payment
seq_Target_Setting_and_Charge_Scheduling	EV communicates charge parameters, cable checking on loop, pre-charging
loop_Charge_control	Power delivery enabled, loop charging and rescheduling until charging is complete, Power delivery disabled
seq_End_of_charging_process	Welding detection phase, session termination
Stop_Communication	End of the HLC
error_handling	Similar strategy applied as that of the ISO standard

Table 7.6: DIN SPEC 70121 Communication sequence between the EV and EVSE

7.2 Integration of Grid Based Model (6.3) With Communication Based Model (7.1)

The integration of the communication based model discussed in section 7.1 with the grid based model in section 6.3 is necessary and crucial to analyze better the behavior of the DC Fast Charging in a more realistic way possible with some hypothesis still considered. This section of study is dedicated to connection made between the two domains which involves a systematic step by step procedure to connect the grid, supply equipment and EV battery together controlled by the standardized charge control and communication protocol in real-time data exchange.

The necessity to integrate one with the other is to make sure that the communication part of the system ensures proper coordination between the EVSE and EV, alongside continuous cable checking, while the electrical part is utilized for close to reality power transfer according to the parameters communicated by the EV to the EVSE constantly according to the protocols. To sum up better, the DC Fast Charging Flow-Chart in figure 7.12 presents a visualization to the integration of both the communication and electrical based domains.

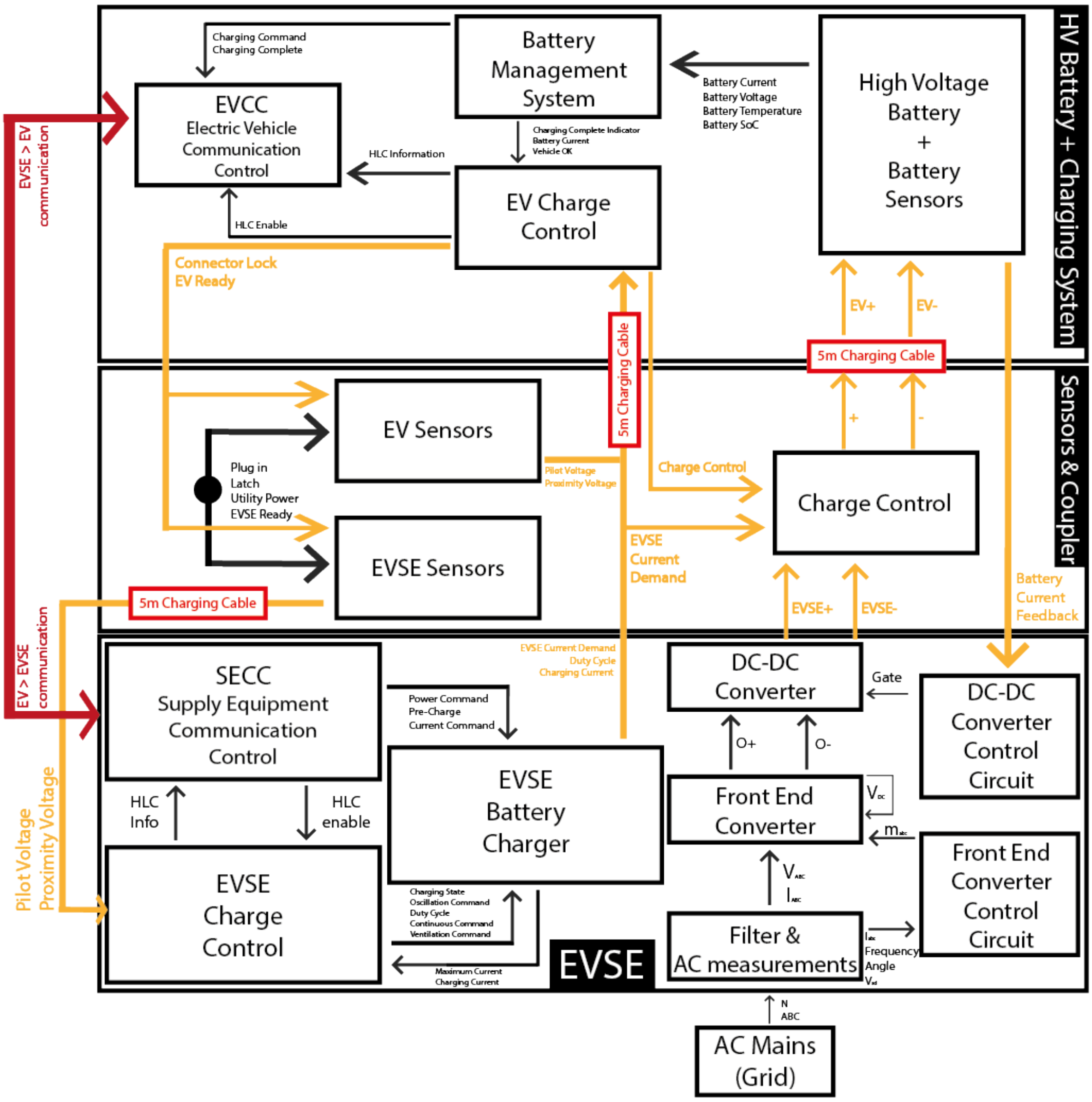


Figure 7.12: Complete Charging System Block Diagram

7.2.1 Model Architecture

As indicated by the figure 7.12, the Grid is fed into the EVSE, while the structure refers to that of the section 6.3, while the High Voltage Battery in section 6.2 is added to the EV Charging System whose input is DC+ and DC-, and the output of the EV battery as discussed before are battery current which is fed as a feedback to the DC to DC converter circuit control for continuous regulation of the current throughout the charging, battery voltage, SoC and battery temperature which are then used by the battery management system for better control over the charging process. Then going into the sensors and coupler subsystem, the DC+ and DC- passing from the EVSE are controlled by the Charge Control block that is used to trigger the electrical switches of DC+ and DC- before the charging cable passes the current into the EV HV Battery, this is done by charge control from the EV control module and the EVSE current demand coming from the EVSE charger, hence enabling current only when desired conditions are met. Taking into consideration the charging cable, a series RLC is connected to both the DC+ and DC- while for the proximity and pilot pins, a transport delay is used. Generalizing the process, the specifications used for the cables, switches and transport delay are given in the table 7.7

Cable and Switch Specifications		
Name	**Value**	**Unit**
Cable Resistance per meter	0.1	Ohm
Cable Inductance per meter	1	μH
Cable Capacitance per meter	100 x 10^(-12)	F
Cable Length	5	m
DC Switch Closed Resistance	1	mOhm
DC Switch Open Conductance	1	μS
Transport Delay	Cable length/Speed of light	sec

Table 7.7: DC Switch and Cable Specifications used

With all the considerations done up to now, the final model is represented in the following figures.

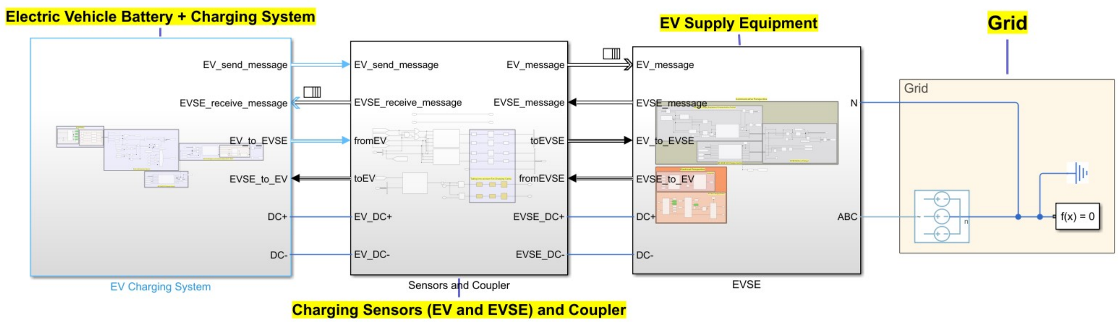


Figure 7.13: Complete Charging System Overall Outlook

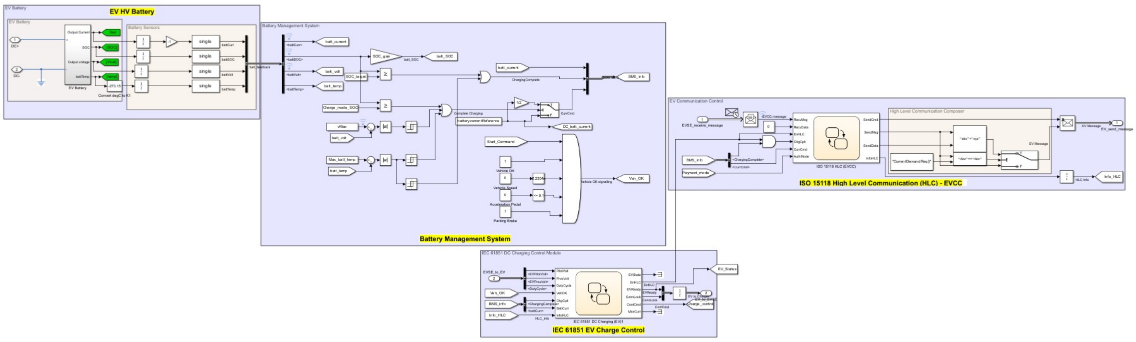


Figure 7.14: Complete Charging System EV Outlook

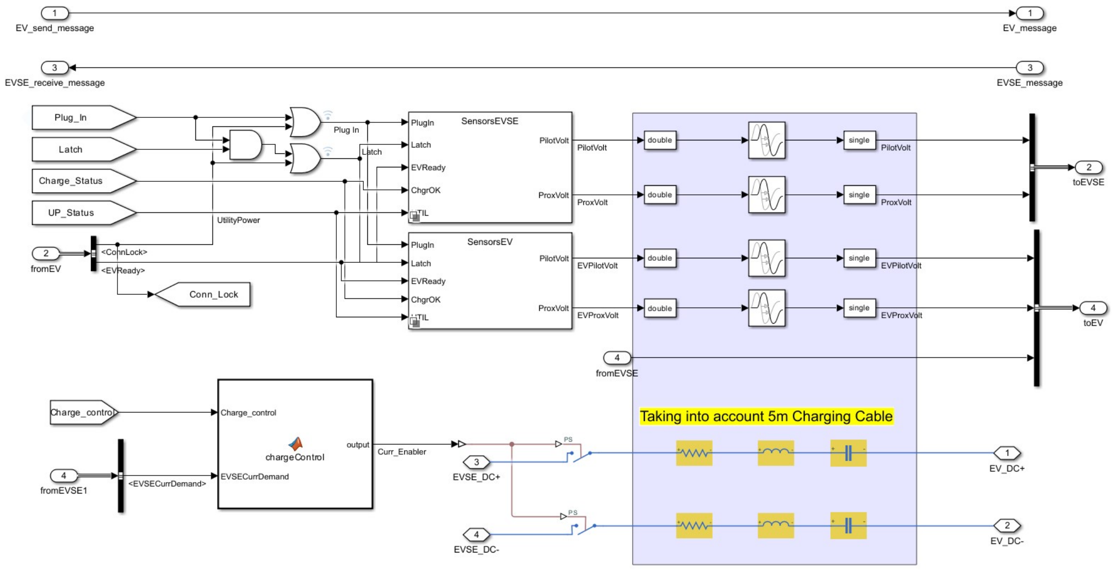


Figure 7.15: Complete Charging System Sensors and Coupler Outlook

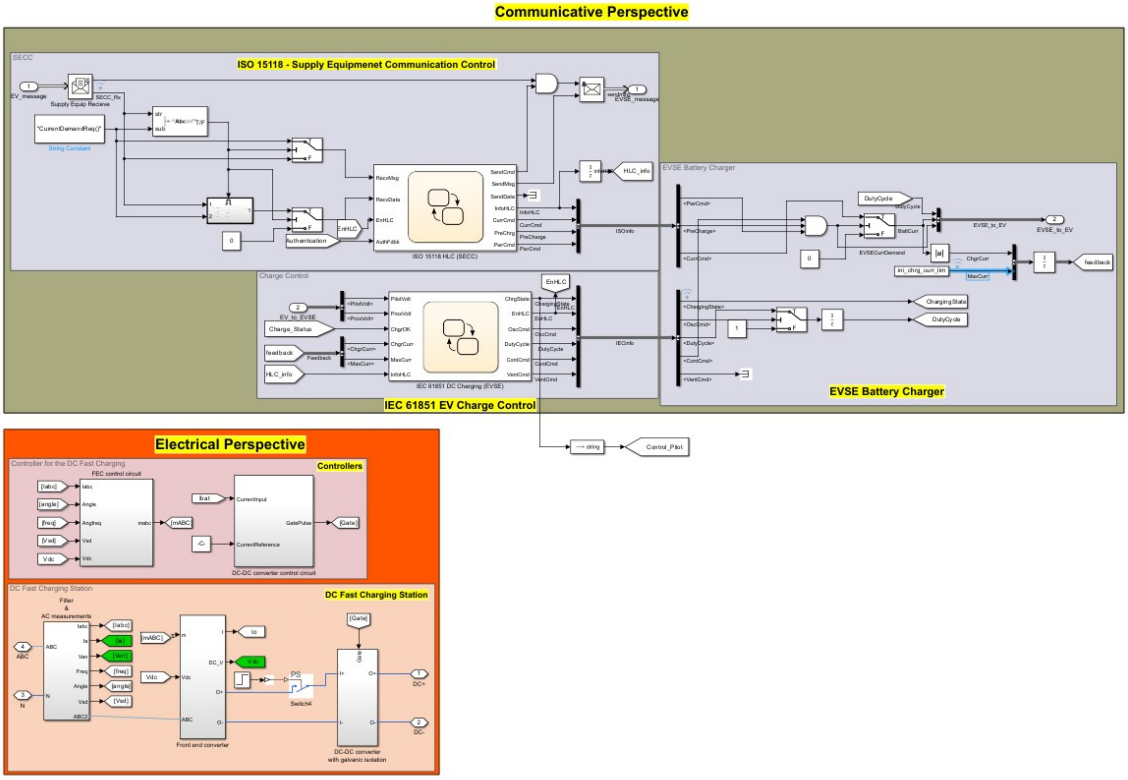


Figure 7.16: Complete Charging System EVSE Outlook

8 Implementation of Different Scenarios

8.1 Short Circuit Scenario

8.1.1 Conditions stated by the Standards

IEC 61851 [25]

- **Section 6.4.3.109 - Control Circuit Supply Integrity:** The power circuit is to be disconnected from its supply to avoid any damage or hazard to charging system if earth fault, **short circuit** or overcurrent conditions take place. The integrity of the power supply for the control circuit is only compromised in case of interruption in the power circuit due to loss of AC supply (Main), this is to take effective measures onto the fault by the circuit control.

- **Section 6.4.3.110 - Short Circuit Test Before Energy Transfer:** Between the DC+ and DC- output lines, the EVSE should perform short circuit testing before initiating charging of EV and closure of EV contactors. This is insured throughout the cable and vehicle coupler so to avoid any short circuit and to manage short circuit within time to avoid any hazard or damage to EVSE or EV.

  For this study, there are two conditions under consideration i.e., if the short circuit occurs before or during the energy transfer procedure, i.e., continuous monitoring of the short circuit, which infact allows the charging system to react immediately either to stop the charging process or by taking other protective measures. And also, even if high quality electrical elements are used within the EV and EVSE, due to degradation over time, short circuit might not occur during initial phase of the charging i.e., before energy transfer but during the charging phase, which could be reasoned due to breakdown due to insulation, connector issues or any other external causes. Finally, even if this section of the standard does not specifically highlights continuous monitoring of the fault but in section 6.4.3.114 i.e., Emergency shutdown does state the implementation of continuous fault detection which could also be done for short circuit, hence when detected implementing emergency shutdown.

- **Section 6.4.3.114 - Emergency Shutdown Procedures:** In case any faulty conditions occurring with in the EVSE or EV, the safety of the entire structure should be ensured by an emergency shutdown which is further characterized into two categories i.e., Controlled and uncontrolled shutdown. Controlled decrement of the voltage and current slopes with continuous communication with the EV about the situation is considered as controlled shutdown, while on the other hand, when fault detected, the charging of the EV is terminated without a controlled slope of current, in certain situations, the vehicle does not receive immediate communications from the EVSE due to immediate effect of the shutdown.

- **Section 102.5.4 - Shutdown Procedures:** The procedure for shutdown is categorized into normal and emergency shutdown. Emergency shutdown is only initiated under fault conditions i.e., short circuit in this case.
- **Annex CC.3.4 - EVSE initiated Shutdown:** Since the considered structure is CCS combo charging used in Europe, in annex CC, the description gives the idea of faulted condition emergency shutdown, i.e., when in emergency, the EVSE should initiate emergency shutdown by reducing the output current to less than 5 A with in 1 second, with descending rate of equal to or more than 200 A/s. Shutdown initiated by turing the control pilot oscillator off.

SAE J1772 [29]

- **Section 6.5.18 - DC Output Short Circuit Test:** Similar to that of IEC standard, before enabling energy transfer between DC+ and DC-, the short circuit testing is performed, here in SAE, it performed within the entire charging cable, connector, vehicle inlet and internal cabling upto the contactors. The condition defined for short circuit is when the current of at least 1 A flows between DC+ and DC- to the current being upto 4% of that of the maximum current rating, it also states, as it should exceed 20 A. In order to perform these checks, it is necessary to have necessary sensing and detection system to identify potential hazardous behaviour from the short circuit and initiate shutdown sequence accordingly, protecting the EV, EVSE and the user.

  Similar to the case followed in IEC standard section, here also the short circuit testing is performed during the energy transfer with the same reasoning as of that one.
- **Appendix F.1.10 - Error and Emergency Handling:** According to the standard, the shutdown is divided into two different types. Error shutdown initiated to protect the EVSE from any potential damage while Emergency shutdown initiated for user protection against faulted hazardous situation. Further error shutdown could be of EVSE and EV originated depending on the fault and on the time it occurs i.e., before or during energy transfer hence transiting the system into a protected and safer state without causing damage to the equipments. Emergency

shutdown on the other hand only initiated when faster and robust response. The main priority remains here to disable the connection from the power even at a cost of eliminating communication between EVSE and EV.

- **DIN SPEC 70121:2014 Integration:** As discussed before, the SAE model follows DIN SPEC HLC protocol hence the error handling should align with the standard accordingly.

8.1.2 Standards based Shutdown Sequence

IEC 61851

Considering the EVSE initiated shutdown sequence, the following table 8.3 indicates the step by step procedure followed to shutdown in case of fault such as short circuit in this case (Annex CC.3.4) [25].

EVSE initiated Emergency Shutdown (CC.3.4)	
Time-stop	**Description**
T26	During the energy transfer <7a>CURRENTDEMANDREQ and <7b> CURRENTDEMANDRESis communicated between the EV and EVSE, at T26 as soon as the fault (short circuit) is detected, the oscillator turns off, also the DC supply status code triggers the EVSE emergency shutdown. The DC supply output is disabled, considering the severity of the event, the EVSE could also be disconnected from the mains due to any particular damage to the EVSE. With DC supply disabled, the DC output current and voltage decreases.
T27	With in few ms of Oscillator turing off at T27 the EV status code becomes 'not ready' hence the CP goes to state B, and the charge current request signal goes to false as well.
T28	Supply maximum current limit goes to zero
T29	With EV status code going to 'not ready' after a few ms, the EV disconnection device opens, which is also conditioned by the EVSE minimum DC output current of -200 A/s, PEV may open contactors while the current still stays above zero.
T30	EV maximum voltage limit goes to zero
T31	At this time stop the DC output voltage is checked if it is below the 60V limit
T32	At this stage, the connected (not ready) phase is initiated where the vehicle and the EVSE in a stable zone, with <9A>WELDINGDETECTIONREQ and <9B>WELDINGDETECTIONRES
T33	With the DC output voltage within the limits provided by the standard, the connector lock is unlocked with <10A>SESSIONSTOPREQ and <10B> SESSIONSTOPRES.
T34	By unmating, the CP goes to state A

Table 8.1: EVSE Initiated Emergency Shutdown Sequence

SAE J1772

According to standard, F.1.10 Error and emergency handling section describes better the procedure to initiate the shutdown when the short-circuit occurs. As in table F3, error shutdown is initiated when the short.circuit occurs before the energy transfer and in F.1.10.1 Table F4 it states that if the error occurs using the DIN SPEC 70121:2014 communication protocol it follows the Table F5, better described in the table 8.2

EV initiated Emergency Shutdown (F.1.10.1.1)	
Time-stop	**Description**
T300	Continuous communication between EV and EVSE <7a>and <7b> CurrentDemandReq/Res
T300	As the fault is detected, EV requests EVSE for DC output disable by communicating <8a>and <8b>PowerDeliveryReq\Res and ReadytoCharge 'False'
T300 >301	The DC output current should be lower than 5A within 1 second or less
T300 >303	If the current is lower than 5A, EV may initiate charge contactors opening
T302	EVSE should communicate that current is lower than 5 A and has disabled DC output by initiating EVSE_shutdown message and also initiate <10a>SessionStopReq, if not performed within 20 seconds, the EVSE should initiate EVSE initiated error shutdown
T303	CP state changes from C to B and initiate the welding detection phase
T303 >304	EV and EVSE communicates multiple times the welding detection phase with <9a>and <9b>requests and also EVSE should check if the CP has changed to B before sending WeldingDetectionRes <9b>
T304	EV and EVSE completes the welding detection, charging contactors open
T305	The EV should send the <10a>SessionStopReq() to the EVSE after the charge contactors have been opened hence terminating the digital communication
T305 >T306	The EVSE should reduce the present voltage at the DC output to lower or equal to 60 Volts
T306	The EVSE sends the SessionStopRes() <10b>
T306 >T307	EV unlocks the vehicle connectors after receiving session stop response from the EVSE
T307	Un-mating the vehicle connector changing the state from B to A.

Table 8.2: EV Initiated Emergency Shutdown Sequence

8.1.3 Implementation in Simulink Model

IEC 61851

The model established in section 7.2 is modified in order to mimic the short circuit scenario which then enables the EVSE emergency shutdown. The following step by step approach is used as mentioned by the 8.1.

1. **Fault Block:** As in figure 8.1, a fault block is added between the DC+ and DC- output lines before it goes into the coupler and sensors subsystem. The fault block is configured to trigger a temporal short circuit at the desired time or desired duration during or before the charging process which could also be triggered

manually with an external fault trigger, which then goes to a unit delay block with a delay of 1 ms, which is within the capabilities of a modern electronic controller to generate control logic in order to initiate emergency shutdown without any significant damage to the components. Also, IEC 61851-23 indicates the initiation of shutdown within 1 second time frame, but it is considered to be the upper boundary, a response time of a few milliseconds is optimal to avoid any damage as said before. Finally, this could also ensure that during transient the spike or dips are not too massive that could significantly put the EVSE or EV in danger.

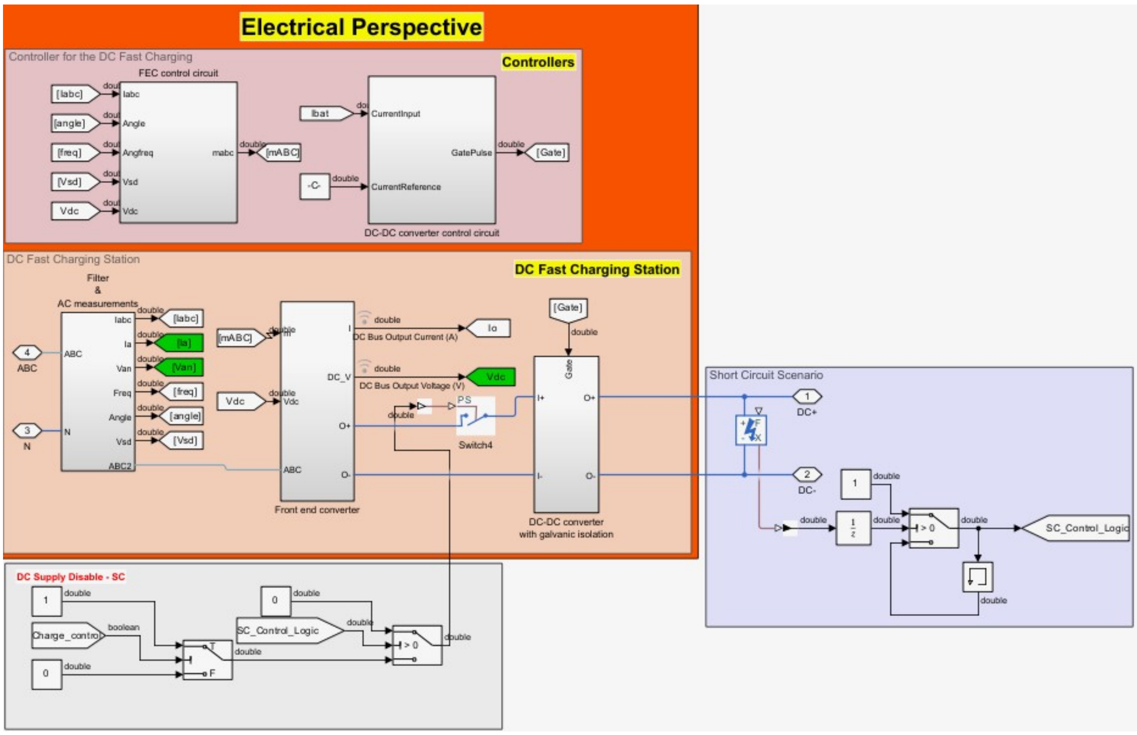


Figure 8.1: Fault Block added between DC+ and DC- on right side

2. **DC Supply Switch:** In figure 8.1, the subsystem at the bottom left shows that upon detection of a short circuit, the system initiates the shutdown procedure in order not to further damage the EVSE and EV, hence the logic presented here, disconnects the DC supply when the short circuit flag is true hence complying with the standard. By disabling the positive line of the DC DC converter, system effectively isolates and bound the fault so to avoid any future damage, mandated by the standard. When the short circuit is detected, the switch disables the flow of DC supply so no current flows into the DC-DC converter, while the charge control is used to turn on and off the switch depending on the system states i.e., EV and EVSE, which is indeed a safe and protected approach in normal and faulted conditions.

3. **Disconnection of EVSE and EV DC+ and DC-:** The figure 8.2 checks if the DC output current is below zero when the short circuit is triggered, then it enables another flag. This flag combines with EV not ready goes into the charge control function which then disables the connection of the EVSE DC+ and DC- with the EV DC+ and DC- as in the figure 8.3. This controlled shutdown prevents damage not only to the EVSE but also so it does not mitigate in to the EV battery. This action is perfomed with the consideration that the transition starting from short circuit detection to current being below 5 A and then disconnecting EVSE with EV should be swift within controlled range as per the standardized instructions.

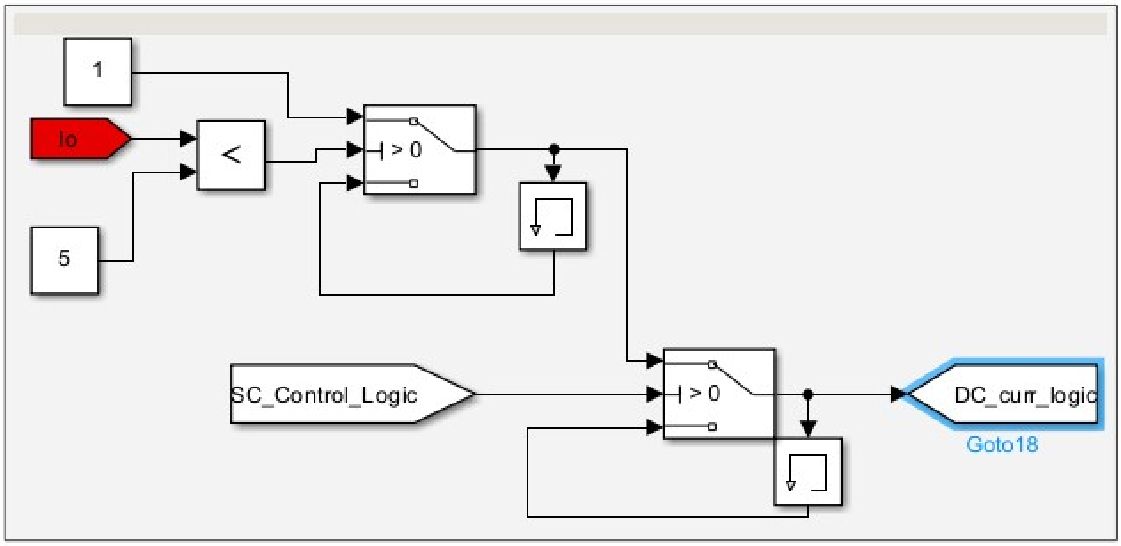


Figure 8.2: Conditioning for the DC Output Current

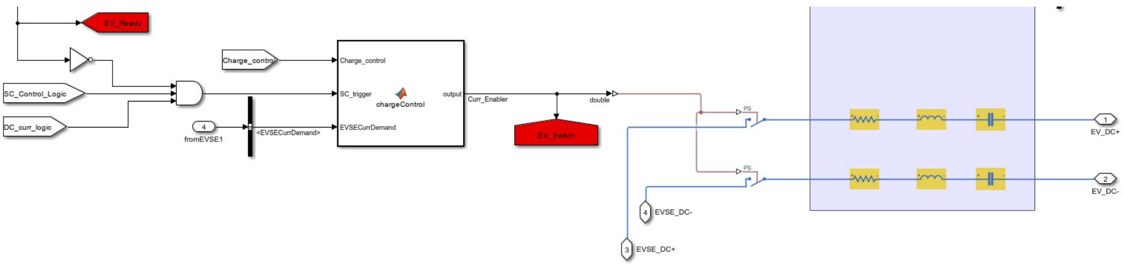


Figure 8.3: Disconnection of EVSE and EV DC Lines

4. **Maximum Current Limit going to zero:** Within the Battery Management System (BMS) as soon as the short circuit logic flag is one, checks are performed and communicated between the EVSE and EV through the CP if the CP charging state goes to B then the maximum current limit goes to zero as depicted in figure 8.4.

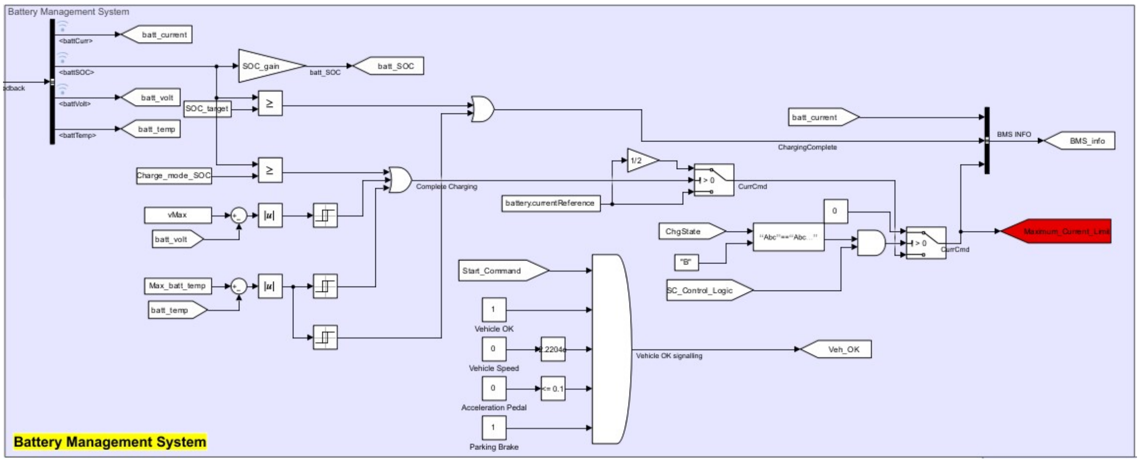


Figure 8.4: Maximum Battery Current Limit goes to zero

5. **IEC 61851 DC Charging EV and EVSE Charge Control Module:** The EU standard state flows for EV and EVSE discussed in the section 7.1.1 are modified in order to add on a condition to initiate emergency shutdown in case of faulted behaviour i.e., short circuit in our case. If the short circuit occurs before the energy transfer i.e., in state B2, it goes to state B1 in which EVSE is not ready while if its in B1, it holds on to that position until further instructions follow, while for the study if the short circuit occurs while charging i.e., in state C1, C2, it is retrieved back to the state B1 immediately so that EV and EVSE are disabled from charging.

6. **ISO 15118 HLC EV and EVSE Communication Module:** Two different loops follow depending on when the short circuit is triggered, if it occurs before the energy transfer and locking of the connectors, the loop goes to the Charging_Stopped_SC in order to directly request the SessionStop communication between the EV and EVSE and then going directly into the Stop_Communication flow state and finally error_shutdown after 200 ms. If the short circuit occurs during the energy transfer, the flag takes the flow out of the loop charging block in to the SC_trigger state in which PowerDeliveryStop, WeldingDetection, MeteringReceipt and finally SessionStop communications between the EV and EVSE are performed, following the same state flow for the Stop_Communication and into error_shutdown after 200 ms.

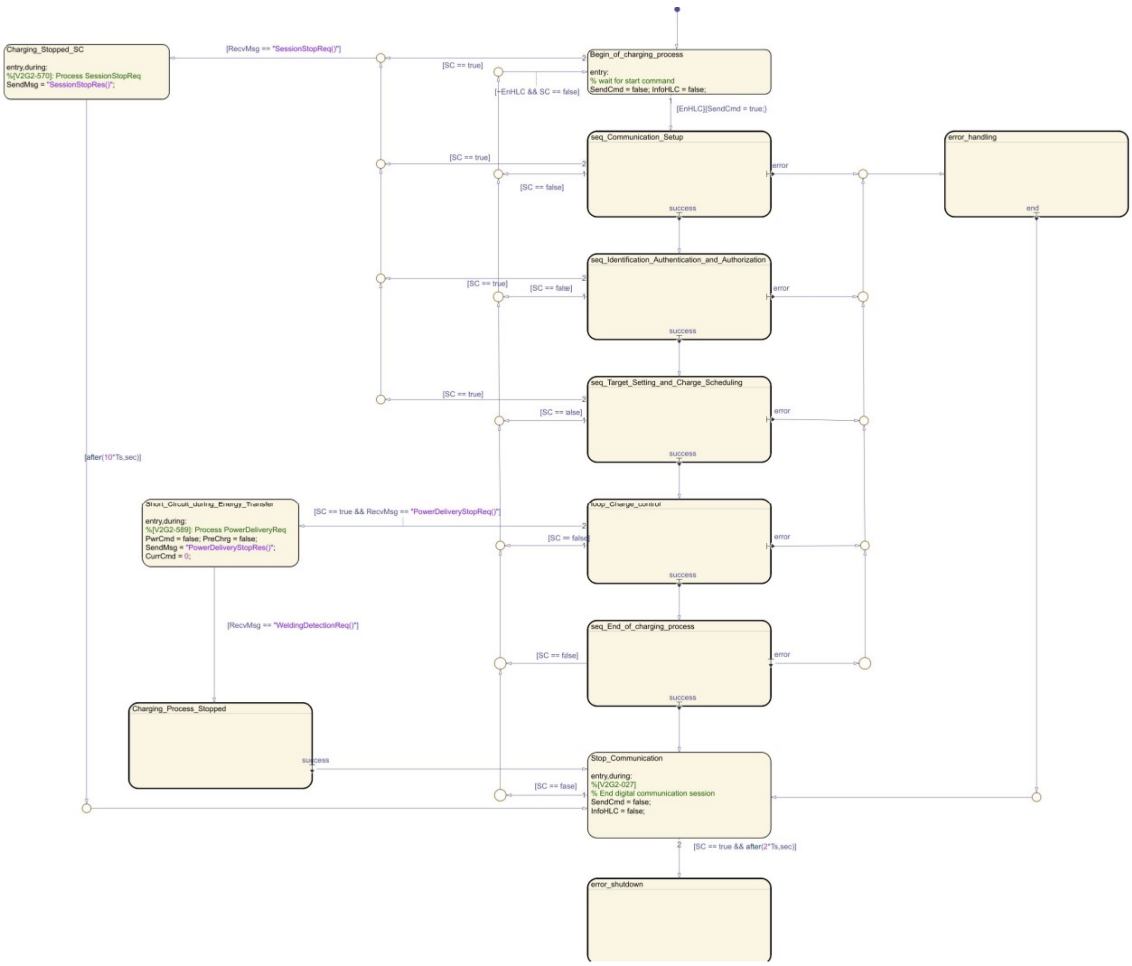


Figure 8.5: ISO 15118 HLC EV and EVSE Communication Module

7. **Connector, CP and Proximity:** Finally, considering the latch, it is turned off as soon as the flag for the short circuit is turned on i.e., one, while the mating is disabled as soon as the EVSE sends the message of "SessionStopRes()" and the connector lock is open as well with a certain delay i.e., 10 ms in order to be close as possible to realistic behaviour, hence it would return the CP state from 'B' to 'A'.

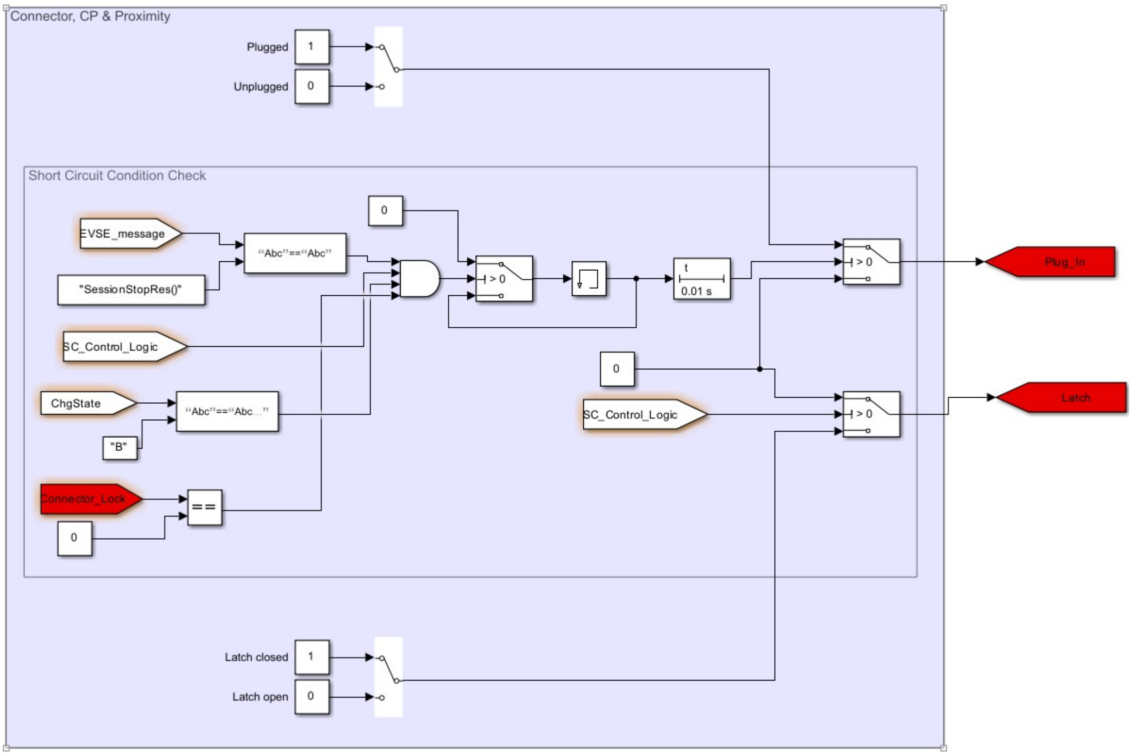


Figure 8.6: Plug in and Latch modification

SAE J1772

The fault block and the DC supply circuit breaker set up as mentioned by the IEC standard in section 8.1.3 is the same in this model as well, with similar characteristics and parameters.

1. **DC Output Current Logic Control:** According to the standard, at T300 the DC output current is checked if it is lower than 5 A when the control logic is true as depicted in figure 8.7, then it triggers the DC current logic. This boolean logic firstly is used to control the latch opening when the short circuit is detected at T301 initiating the error shutdown depicted in figure 8.8. While between the the time stop T300 to 303, first condition is checked is if the EVSE message sent to the EV is WeldingDetectionRes() and if the contactors are closed since this condition is only valid when the energy transfer is perfomed, if this is true along with the CP charge state to be 'B' and ofcourse the DC current logic to be true the charge contactor logic becomes true going in to the chargeControl function which in turns makes the switches between the EVSE and EV DC+ and DC- disconnect accordingly.

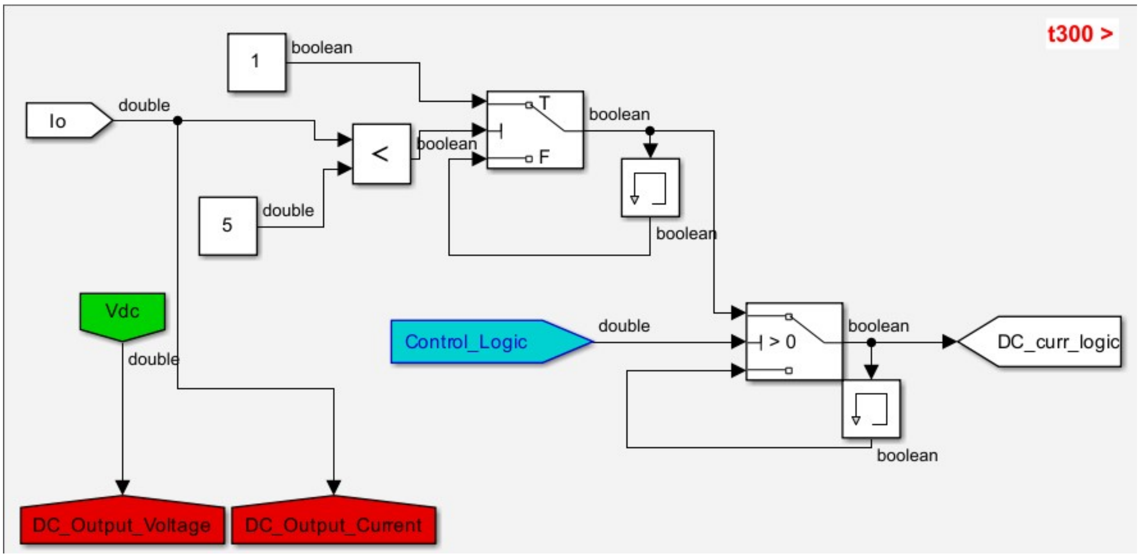


Figure 8.7: DC Output Current Logic

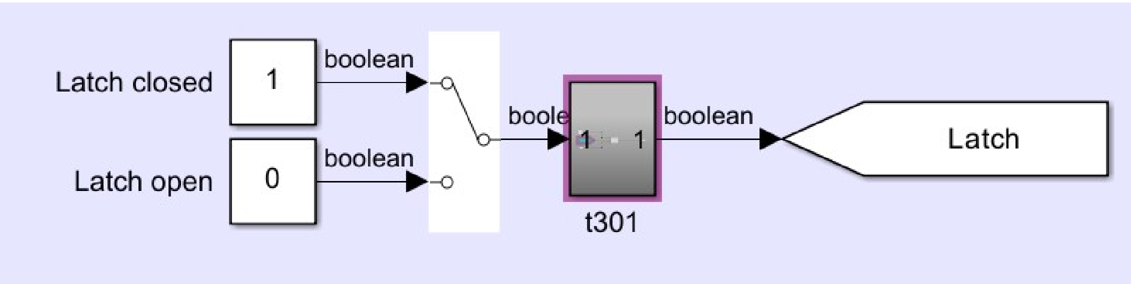


Figure 8.8: Latch Opening

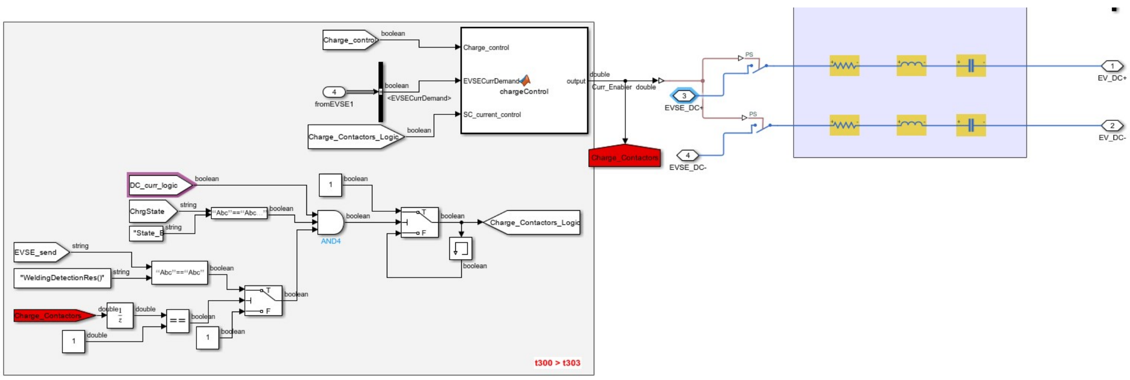


Figure 8.9: DC Lines Contactors Opening Logic

2. **EV Target Current:** At T300 as per the sequence of the error shutdown, the EV target goes to zero in the BMS when the short circuit control logic becomes true.

3. **IEC 61851 DC Charging EV and EVSE Charge Control Module** Similar to that done with the state flow in the IEC standard one in section 8.1.3, here the EV and EVSE states are also altered. When the fault control logic is true, the state either be B2, C1, C2 and C3, it is returned to state B1 in 100 ms where the EVSE is not ready.

4. **DIN SPEC 70121:2014:** If the short circuit occurs before the energy transfer, the communication flows into the Charging_Stopped_SC state where Session-StopReq() is sent by the EV to the EVSE and after receiving the response, it passes into the Stop_Communication state, where after 200 ms error shutdown terminates with the error message. While if the short circuit occurs for a few ms from the loop_Charge_control the communication flows into the SC_trigger state where PowerDeliveryStopReq() is sent to the EVSE followed by Welding-DetectionReq() and SessionStopReq() as per the standard protocols for the error shutdown following the same loop of Stop_Communication, going in to error_shutdown state as depicted in figure 8.10.

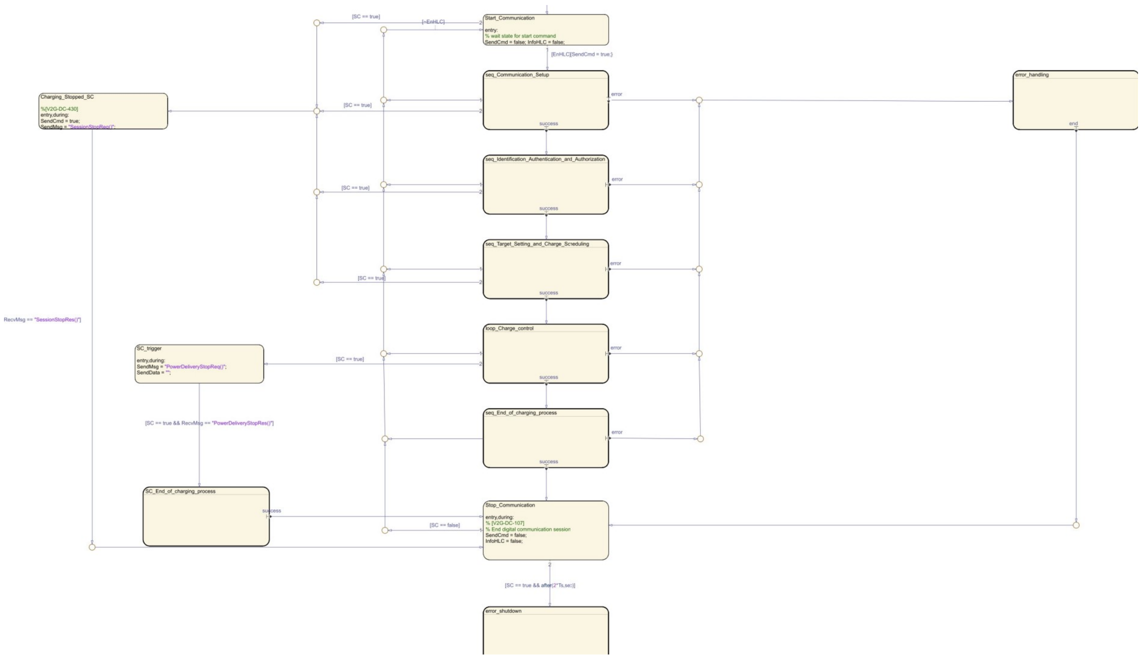


Figure 8.10: Modification in the DIN Communication Protocol flowchart

5. **Un-mating Logic:** As per the standard sequence, the procedure ends with un-mating which in fact changes the CP state from B to A, which is done as soon as the connector lock opens, charger contactors logic is true, and when the EVSE terminates the process by the SessionStopRes() as said in the standard table. The figure 8.11

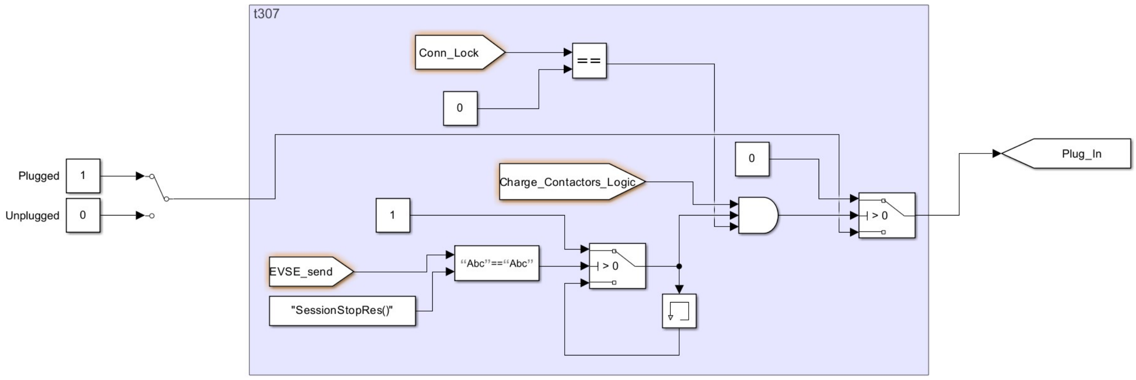


Figure 8.11: Un-mating to change state from B to A

8.2 Load Dump Scenario

8.2.1 Conditions stated by the Standards

IEC 61851 [25]

- **Section 101.2.1.7 and CC.6.3 - Load Dump Case:** The worst case scenario of load dump is when the current reduces from 100% i.e., nominal value to 0% usually caused by the disconnection of the EV battery from the EVSE while the other other EV loads stay connected. During this condition, the main concern is the voltage overshoot due to reduction in the current and according to IEC 61851-23 standard the voltage overshoot should not be more than 110% of the EV communicated maximum charging voltage and also the maximum slew rate of the output voltage should not be more than 250V/ms, which is considered to ensure controlled voltage increment, which should not damage the EV charging system or the EVSE. For this study, CC.6.3 specifies the details as mentioned above regarding the overshoot limit. This bound is necessary for preventing damage to the EV components i.e., battery and electronics, that are over-voltage sensitive.
- **Section CC.6.2 - Over-voltage protection mechanism:** When the output voltage is greator than that of the limit communicated by the EV for more than 400 ms, EVSE initiated emergency shutdown is engaged. In physical sense, the EVSE monitors the output voltage while charging is done. If the load dump occurs, the system must of able to detect the voltage data when it occurred and

when it goes above the threshold given by the standard i.e., 110% maximum voltage, it goes into initiating the emergency shutdown.

SAE J1772 [29]

- **Section 6.5.30 - DC Output Load Dump:** The SAE standard has two separate limits of the voltage spike due to load dump.

  1. EV rated maximum voltage $>$ 500V: The voltage overshoot should not be greater than the 110% of the maximum voltage communicated during the ChargeDiscoveryParameter.
  2. EV rated maximum voltage $\leq$ 500V: The voltage overshoot should not go above the rated maximum voltage plus 50 V.

  For this research, the DC Output voltage is below 500V hence the second condition will be considered.

- **Section 6.5.24.2 and 6.5.24.3 - Over-voltage Conditioning:** The standard highlights two different shutdown sequences when considering the over-voltage scenario for the protection of EVSE and EV i.e., Emergency Shutdown and Error Shutdown.

  1. EVSE should trigger emergency shutdown during the energy transfer within 1 ms, of the DC output voltage exceeds the limit as mentioned in the standard section 6.5.24.2 table 21 for higher than 9 ms. Here since the **U** considered is lower than 500 V, hence the threshold voltage considered is 550V.
  2. EVSE reaction to the over-voltage is also based on the duration of the voltage after exceeding the maximum voltage which could be used to trigger error shutdown. For more details section 6.5.24.2 table 22 highlights the possibilities.

In the current implementation, voltage overshoot is continuously monitored and checked if after the first 3 ms of the load dump, it does not exceed the limits mentioned by the standard depending on the maximum voltage of the battery. For this study, the maximum voltage is 445V hence the limit is 495V.

8.2.2 Standards based Shutdown Sequence

IEC 61851

In the case study of load dump scenario for IEC standard, when battery voltage exceeds the 110% of the maximum voltage limit set by the standard. it is then sent to the load dump shutdown flag with a delay of 1 ms which then initiates EVSE initiated shutdown. The shutdown sequence followed after this is the same as that of the table 8.1.

The choice of this approach has advantages and considerations that should be kept in mind. Firstly, by initiating emergency shutdown, the battery and the EV components health and safety is prioritized, lowering the damage risk due to over-voltage condition. Secondly, preventing further increase in the voltage results in lower stress on the electronics and insulating components, beneficial for the EVSE and EV battery aging. On the other hand, immediate emergency shutdown increases demand on the control system i.e., EVSE should continuously monitor the voltage and as soon the over-voltage condition is detected, the shutdown should be done with minimal delay, requiring highly reliable voltage sensors and control logic, also, it also increases the possibility of unnecessary interruptions due to momentary spikes which could last for not so long that could physically harm the system, hence inconvenient for the users.

Since the primary goal is to have EV battery and its component protection, hence the emergency shutdown is justified with this. This becomes more significant if the EVSE is intended to charge the vehicle that have strict voltage and current tolerances for higher electrical stability.

SAE J1772

EVSE initiated Emergency Shutdown (SAE J1772 Table F7)	
Time-stop	**Description**
T500	As soon as the fault is detected, the S2 latch opens
T500 >T501	The EVSE starts the shutdown within the trigger time that is 9 ms
T501	The start of the EVSE initiated emergency shutdown
T501 >T502	EVSE turns off the CP oscillator in 10 ms or less
T501 >T503	EVSE reduces the DC output <5A and also disables the DC output with in 20 ms or less if not done already
T501 >T506	EVSE should reduce the DC output voltage to less or equal to 60 V
T502 >T507	EVSE and EV may maintain HLC
T506	The present voltage at the DC output between the DC+ and DC- should be lower than 60 V DC
T507	Vehicle connector un-mating would result in CP change from B to A

Table 8.3: EVSE Initiated Emergency Shutdown Sequence

8.2.3 Implementation in Simulink Model

IEC 61851

The model established in section 7.2 is used, which contains the same control logic as that of the short circuit IEC standard logic i.e., EVSE initiated emergency shutdown in section 8.1.3 while the load dump set up is discussed below.

1. **Load Dump Set-up:** In the Matlab main file, the characteristics of the load dump condition is defined i.e., the duration, start time and the maximum voltage that needs to considered in order to execute the emergency shutdown. Then this is used in simulink model within the EV high voltage battery system to trigger the load dump at the desired time and duration. In figure 8.12, at the desired time the load dump flag triggers the switch in the positive terminal for the desired duration mentioned, while two RC circuits are added parallel to the switch to protect the switch and the system from potential damage from voltage spike, a diode could also be used in this case. When the load dump is initiated, Battery is suddenly disconnected from the EVSE, the current transfer is interrupted, giving rise to high-voltage spike which is due to inductance in the circuit, this could be high enough to put the electronics and components of the electrical system of the EV in danger. The RC circuit dissipates the energy stored by the inductance. The resistor releases the energy as heat while the capacitor absorbs the voltage spike

hence reducing the voltage spikes to less damaging levels. When the switch opens up, the capacitor in the transient stage provides a low impedance way for the current, hence the voltage rise slowly, lowering the voltage peak, while the resistor hinders the current flow into the capacitor, hence higher dissipation of energy, good for the circuit stability.

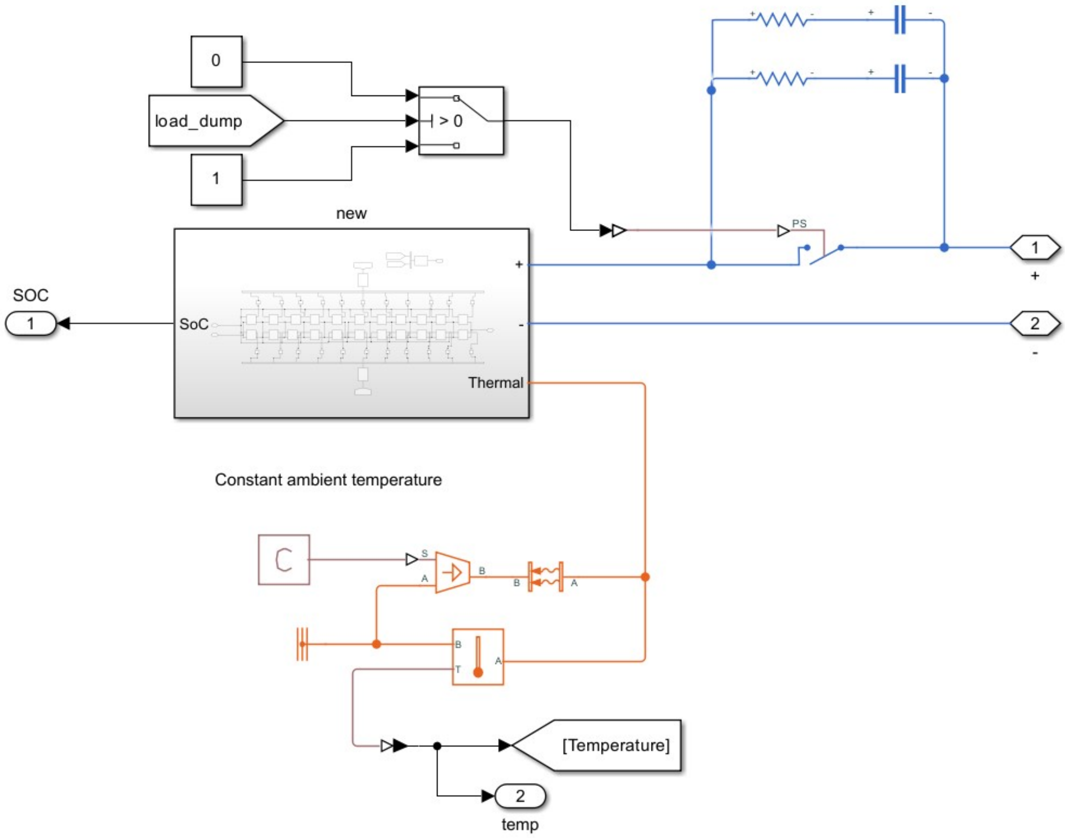


Figure 8.12: Load Dump set-up at the terminals of the battery

2. **EVSE Initiated Emergency Shutdown:** As in figure 8.13. The voltage output from the HV battery is continuously monitored and compared to the maximum value communicated by the vehicle to the EVSE. and if the voltage becomes higher than the maximum value, it triggers the EVSE emergency shutdown with a certain delay of 1 ms in order to comply with a more realistic approach, while the rest of the shutdown procedure is as per the standard which was discussed in the table 8.3.

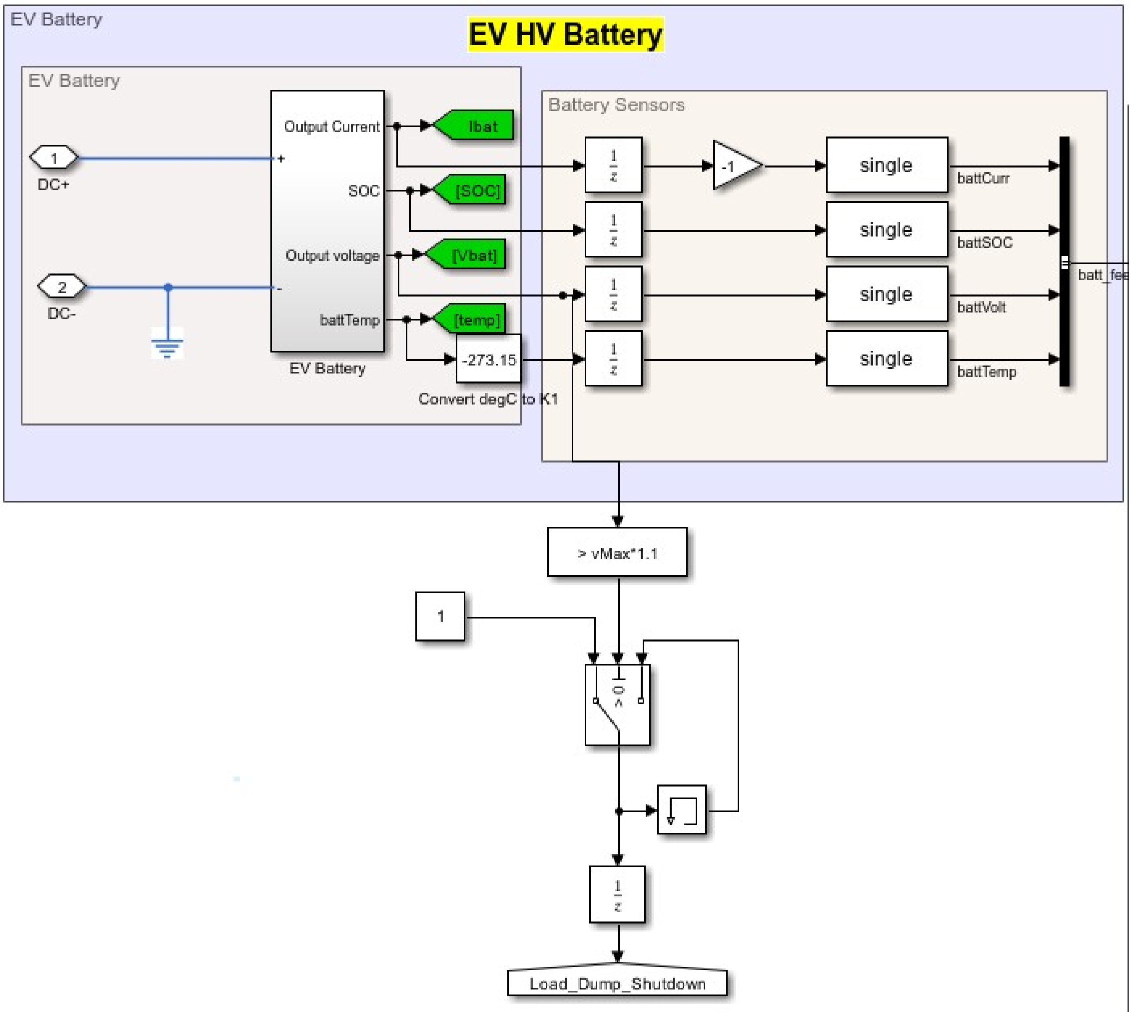


Figure 8.13: Load Dump Control Logic to initiate EVSE Emergency Shutdown

SAE J1772

In the following there is step by step procedure to initiate EVSE Emergency Shutdown with regards to load dump detection in parallel to the SAE J1772 Standard approach. The load dump set up at the terminals and parameters used are the same as that explained in the IEC in section 8.2.3

1. **Load Dump Conditioning:** The battery output voltage is monitored and compared to the threshold mentioned by the standard i.e., 550V and then the second condition is checked i.e., if the voltage remains over this threshold limit for more than 9 ms, if so, then the emergency shutdown flag turns one and then used for the control logic. The figure 8.14

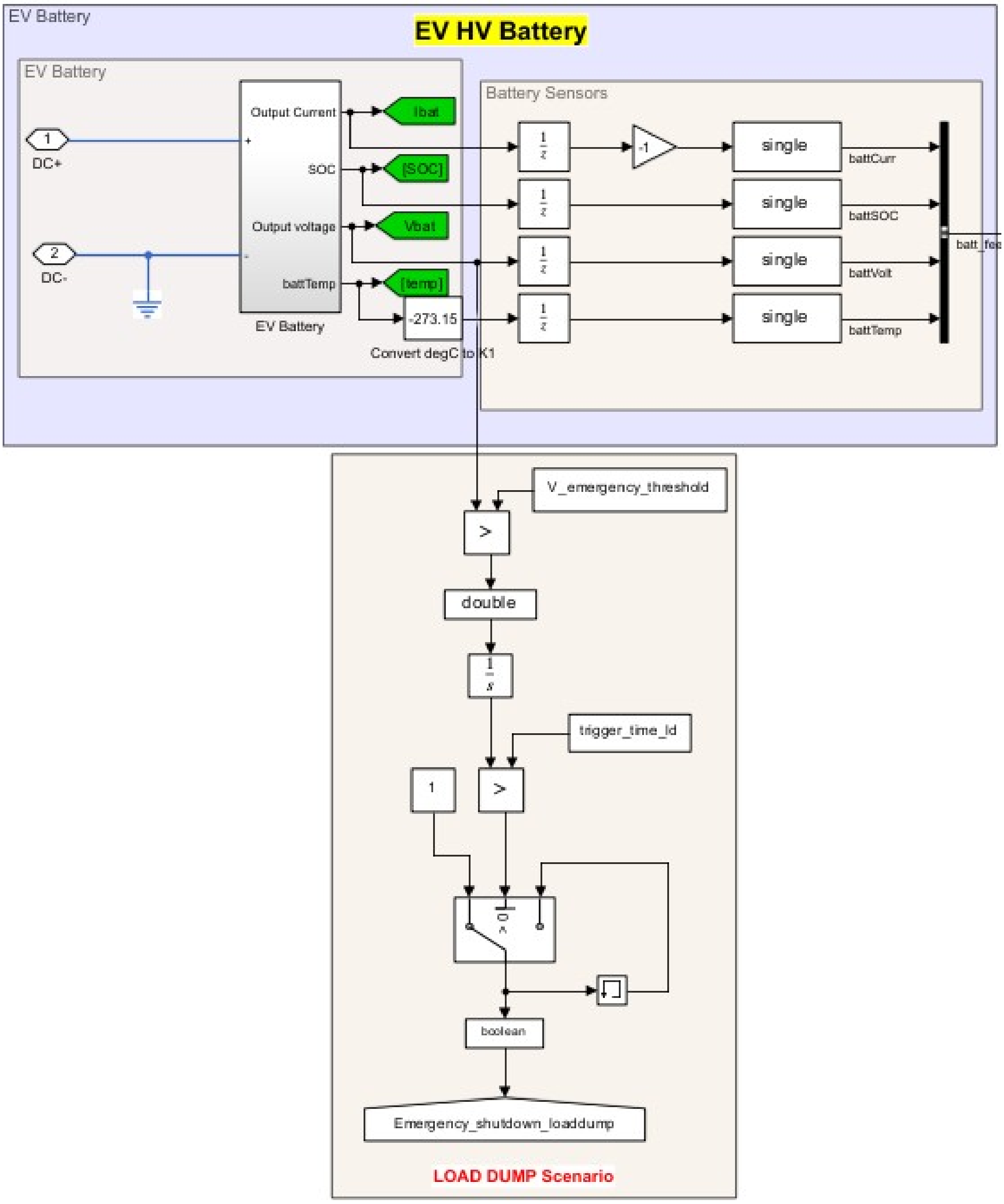


Figure 8.14: Load Dump Control Logic to initiate EVSE Emergency Shutdown

2. **Charging Control Module and Communication Protocol:** The flag mentioned before is then used by the SAE EVSE charge control with a slight delay of 7 ms which turns the oscillator off and the duty cycle goes to one hence the CP state changes from C to B1, indicating that the vehicle is connected with EVSE

but both of them are in not ready state. While the same flag is used by the EV with a delay of 10 ms in order to receive the instructions from the EVSE for the shutdown.

The communication protocol with the EVSE is modified to react to the load dump scenario during the loop charging and initiate communication based emergency shutdown. Hence first the power delivery stop request is responded by the EVSE and t hen the welding detection is communicated, finally ending the charging process by stopping the session and ending the communication.

3. **Connector, CP and Proximity:** The Latch is disconnected as soon as the emergency shutdown due to load dump is detected, while the un-mating is performed as the last step hence only when the connector lock is open changing the state from B to A as seen in the figure 8.15.

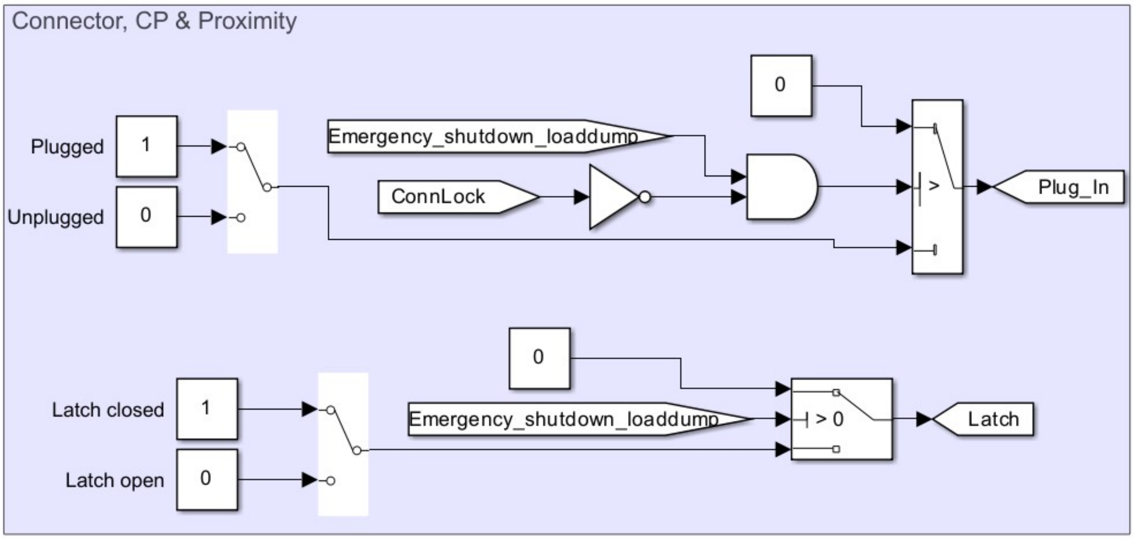


Figure 8.15: Control Logic for Latch and Un-mating

4. **DC Output Current Check:** The DC output current is then checked if it is smaller than 5 A in figure 8.16 is then used by the charge control function to disconnect the DC+ and DC- charge contactors.

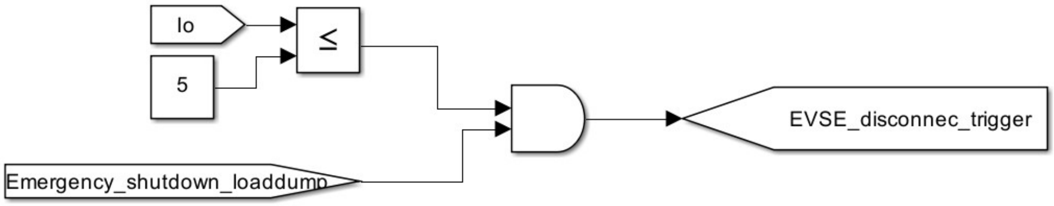


Figure 8.16: Control Logic for Latch and Un-mating

9 Results Discussion

9.1 Normal Charging Start-up Results

9.1.1 IEC 61851

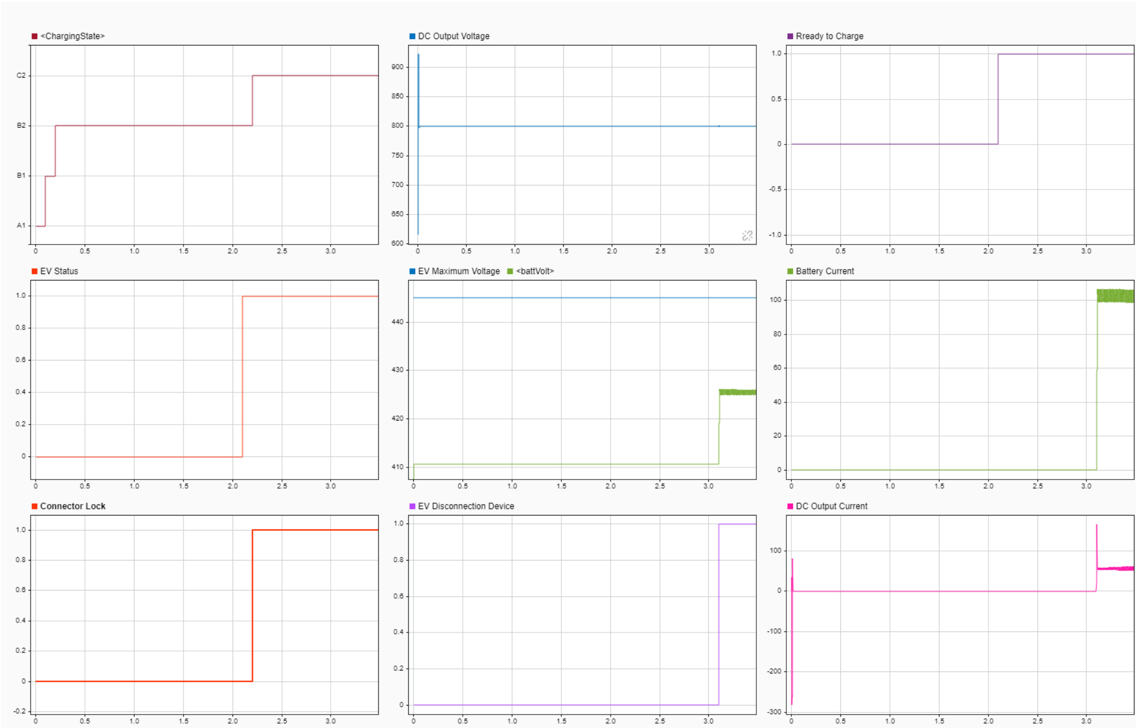


Figure 9.1: IEC 61851 Normal Start Up

- Considering the CP charging state A1 when the connection between the EVSE and EV is awaited, and the oscillator is turned off with duty cycle being 100% and also the EV control command (Readytocharge) is turned off. When the Latch S2 is enabled, the Pilot Voltage communicates between the EV and EVSE while being between 2V and 10V while the Proximity Voltage is between 1.23V and 1.82V, hence changing the state from A1 to B1.
- In B1 where the vehicle and EVSE are connected and not ready to charge, the high level communication is disabled. When the EVSE power is available while the Proximity Voltage remains between 1.23V and 1.82V, within 100 ms the state changes to B2.

- In B2, 9V PWM communication is used between the EV and EVSE where the EVSE is ready and when moving from B1 to B2, HLC is enabled and Duty Cycle changes to 5% with the oscillation command turned on. For the vehicle when the PWM is detected and communication is maintained, the EV Status i.e., Vehicle is ready or not turns true as seen by the figure 9.1.
- The duty cycle is checked by the EV if it's between 4.5% to 5.5% and if the HLC is enabled and vehicle is in okay condition then the CP state further changes to C2 which is the charging state in which 6V PWM is used, as can be seen by the 9.1. In this state connector is locked and current voltage status is communicated between the vehicle and EVSE.
- with connector being closed, the EV DC+ and DC- lines pass on the charging to the EV battery only when the EVSE enables the power command and communicates with the EV the current demand along with the charge control as seen by figure 9.1. When it is enabled, then only the DC lines passes the current to the EV battery starting the charging at around 3.1 second.
- Spike can be observed at the FEC DC output current which is due to several reasons.
  1. At the start of the charging phase, the filtering capacitors in the transient phase fetch large amount of current to match the level of voltage first of the DC bus, also known as the inrush current, causing a spike in the DC bus current.
  2. When considering low SoC of the battery, it initially absorbs high current to go to the optimal battery current as communicated by the vehicle, hence the spike could be associated to the battery reaching the optimal charging voltage.
  3. The voltage and current of the FEC is maintained by the control system, during the transient a spike is observed due to the transient response reaching a stable optimal charging level.
  4. MOSFETs and IGBTs switches used in the FEC and DC to DC converters during the switching transient causes a current spike, which could be controlled by the control systems of FEC and DC-DC, a small transient spike observed here could be neglected but for a large transient some optimization of the control system is suggested.
- Some ripple effect is observed at the battery output current and voltage which is due to several reaons as mentioned below:

1. DC-DC converter is used to smooth the current out going in to the battery, but in reality small ripple maybe able to pass into the battery only if the inductors used in the converters are not optimized enough or due to low switching frequency.

2. While the voltage ripple generated is associated to the capacitors used in the converter, the ripple effect is minimized by optimizing the capacitor value or through high frequency components filtration.

3. The battery current is also affected by the internal construction of the battery used mainly associated to the internal resistance which has higher influence on the current than on the voltage. Also, the battery can be considered as a capacitor of large capacitance which in-fact reduces the battery voltage ripple smoothly than compared to the current.

9.1.2 SAE J1772

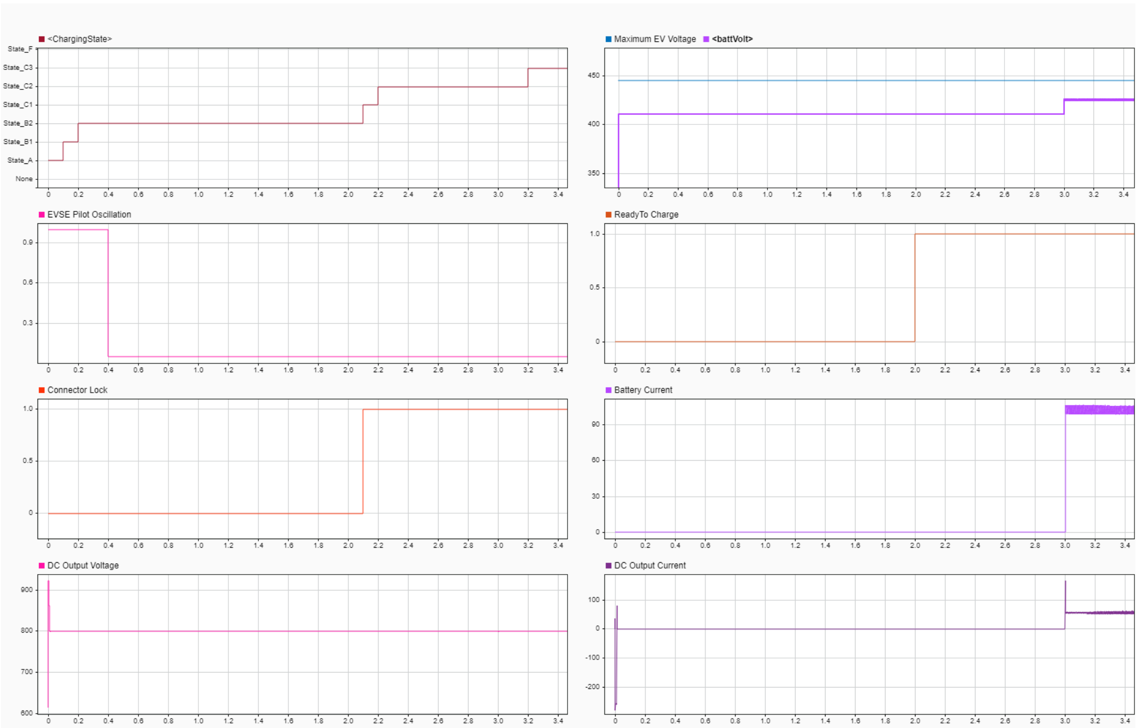


Figure 9.2: SAE J1772 Normal Start Up

- CP status is state A during the initial starting phase, where EVSE Pilot Oscillation is 100%, hence indicating the vehicle and EVSE waiting for the connection to happen.

- When the Pilot Voltage goes in between 2V and 10V and the Proximity Voltage between 1.23V and 1.82V as communicated by the charging system and EV, the CP changes to state B1, in which the vehicle and EVSE are connected but not ready to charge, at the exit of this state HLC is enabled.
- While the Proximity Voltage remains between 1.23V and 1.82V, a check is maded if the EVSE is ready to charge or not, and within 100 ms, EVSE changes the CP state to B2.
- B2 state is considered to be of the longest duration state in the pre-charge phase before the charging actually begins, in this state HLC is enabled and the oscillator is turned on at 5%. While all the communications and safety protocols are exchanged between the EV and EVSE and when the checks are finished the EV ReadyToCharge is true and the Pilot Signal changes the voltage oscillates between 5V and 7V.
- Hence state C1 state is on in which EV and EVSE are ready to initiate charging, hence the connector locks first and the maximum current is continuously check as a function of the duty cycle.
- After checking the S2 Latch being closed i.e., 100 ms, the state C2 is enabled in which the contactors close and further the check of EVSE current is made if it is less than 0.1 A and if the EVSE current is lower than the maximum limit communicated by the EV.
- When these conditions are met, the CP Pilot changes the state to C3, enabling the charging at around 3.2 seconds as indicated by the figure 9.2

9.1.3 Comparison

- IEC ensures that the initialization phase is well-defined and ordered in which as seen by the graphs there appears to be a systematic transients through different phases such as checking of voltage and current to be within reasonable ranges before approaching further in the stages, proving safety to be prioritized before actual charging begins as mentioned in the comparison in section 5.3. While the SAE standard as seen by the graphs shows a progressive yet rapid changes as compared to the IEC standard, due to different control logic that prioritizes the fast charging readiness hence minimizing the charging starting time. Also it prioritizes rapid voltage stabilization and minimum to low current flow transient while starting the charging. Hence, in conclusion the IEC has longer initialization phase. The different charging starting times can be seen in the figure 9.3.

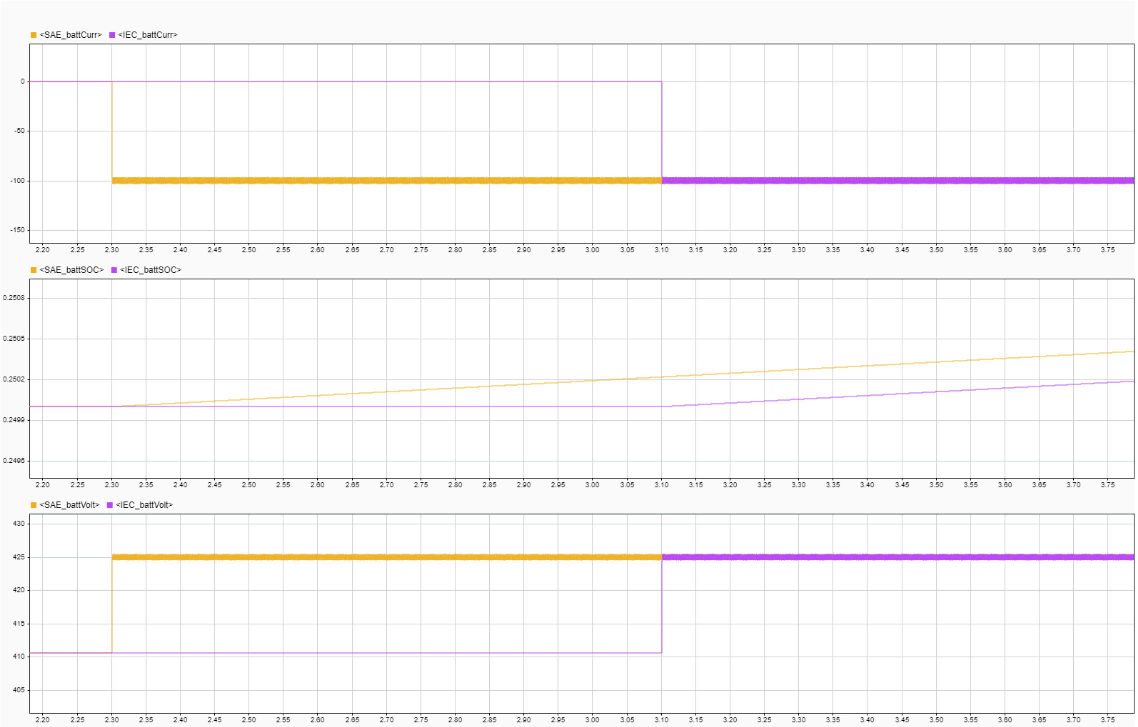


Figure 9.3: Charging Starting Time of IEC and SAE

- As the figure 9.3 also suggests the effect of different communication protocols used for the two different standards. IEC model used the ISO based model which is more descriptive requiring higher level of communication during the initial phases for safety, protection and verification purposes. While the SAE J1772 uses the DIN based model which when compared to the IEC is more aburpt and direct during communication phase between the EV and EVSE, hence the readiness is increased in SAE lowering the duration of the initialization and verification step.

- **Effect on Charging Process:** In conclusion, comparing the SAE and IEC, when quick charge is required SAE is beneficial due to faster initialization process. While the IEC as opposed to SAE posses higher stability and safety before and during charging process, beneficial for battery health and EVSE components and reliability.

9.2 Short Circuit Results

Before mentioning the results, two possible scenarios are considered, i.e., before energy transfer and during energy transfer with short circuit duration of 2 ms which is a short duration yet it lies within the fast response time of currently used charging systems, hence the breaker used should be able to react within the time necessary without any potential damage to the system or the vehicle battery. This duration is also necessary valid to take in to consideration quick transient response of the voltage, current and other parameters. Also the standards specifies their respective conditions and reaction time due to over-current and over-voltage scenarios such as discussed above in SAE where it should react with 1 ms to over-voltage to initiate emergency shutdown. And considering practical world implications a 2 ms short circuit can be used to put the system to test in order to check it’s rapidness under high stress with their respective standards and communication protocols.

9.2.1 IEC 61851

Before Energy Transfer

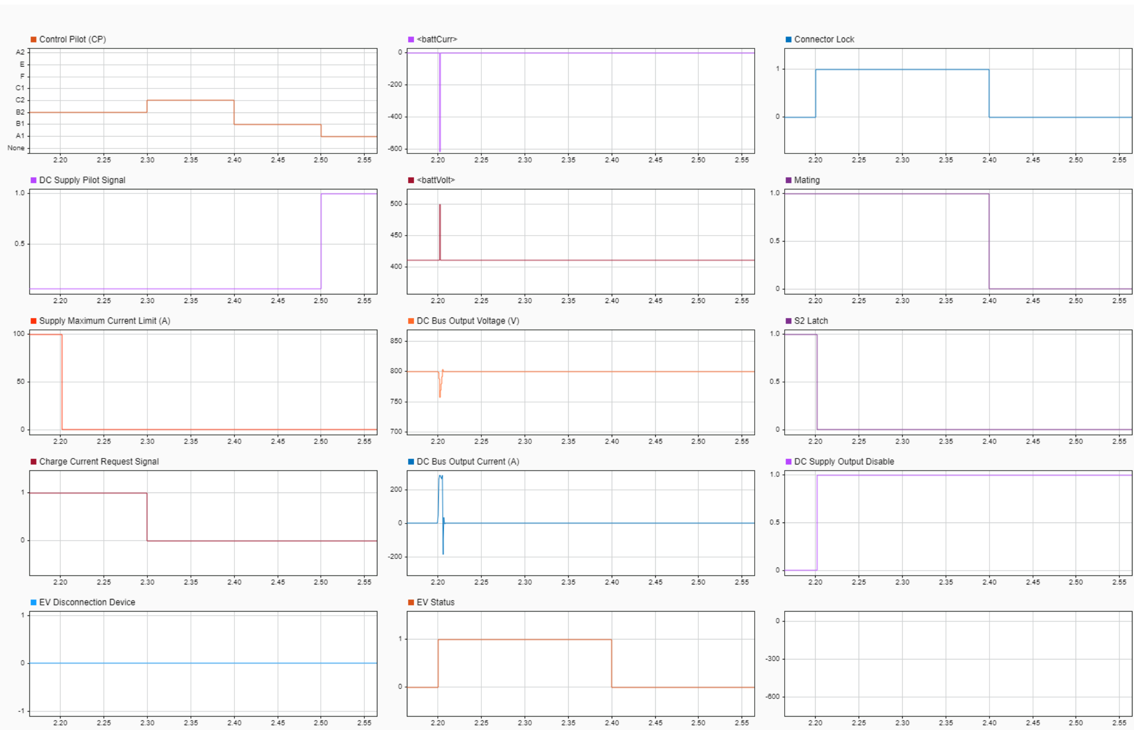


Figure 9.4: IEC Short Circuit Detection Before Energy Transfer Close Up

As the figure 9.4 shows a close up of the short circuit occurring at 2.20 second before the start of the energy transfer and according to the IEC standard EVSE initiated emergency shutdown is initiated. Following is step by step analysis of the process as per the table 8.1.

1. The short circuit is initiated at 2.5 second before the actual start of the energy transfer which is for 2 ms and EVSE due to continuous monitoring detects this with in 1 ms of detection and turning off the latch S2 and DC Supply
2. Considering the state of CP changes to ’B’, the maximum current limit goes to zero along with the charge control i.e., current supply from the EVSE to EV is disabled.
3. Within 100 ms, the DC supply pilot signal changes from 5% to 100% disabling the oscillator, hence the connector lock is unlocked, with EV ready going to false as well.
4. With the consideration of DC output current being lower than 5 and EV ready going to not ready, the EV switch disables the DC lines to the battery.
5. Finally, when the EVSE sends message for ’SessionStopRes()’, charging state remains in ’B’ and the connector is unlocked with 10 ms the un-mating is done changing the state from ’B’ to ’A’.

During Energy Transfer

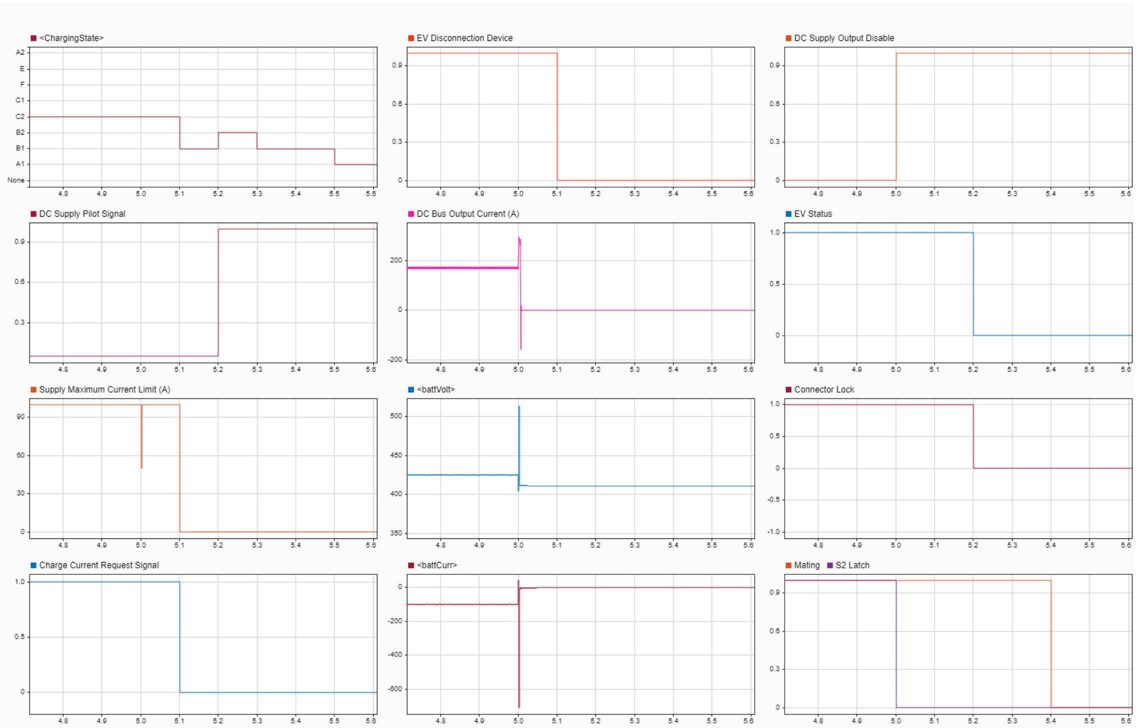


Figure 9.5: IEC Short Circuit Detection During Energy Transfer Close Up

- At 5.0 second, the Short Circuit occurs for 2 ms, as can be seen in the graph 9.5, the Battery Voltage and Current is affected by the short circuit before the DC is disabled. Since the Battery Voltage goes above the maximum voltage accepted by the EV battery the Supply Maximum Current Limit have a dip to 50A in avoidance of battery damaging. At the instance of DC disable i.e., the detection of the short circuit, the EVSE disables the latch S2 also according to standard specifications.
- Further ahead 100 ms, the charging state changes from ’C2’ to ’B1’ so to change the charge current request signal from EV to zero and the DC lines are EV disconnection device is enabled with maximum supply current limit communicated by the EV goes from 100A to 0A.
- 200 ms from the short circuit detection, the EVSE shutdown initiation put the EV status to false and unlocks the connector lock.
- When the charging system stabilizes and EVSE sends response of Session Stop to the EV, the un-mating is done, changing the state from ’B’ to ’A’ at around 5.5

seconds. Hence, the total duration from short circuit to state ’A’ after shutdown is around 500 ms.

9.2.2 SAE J1772

Before Energy Transfer

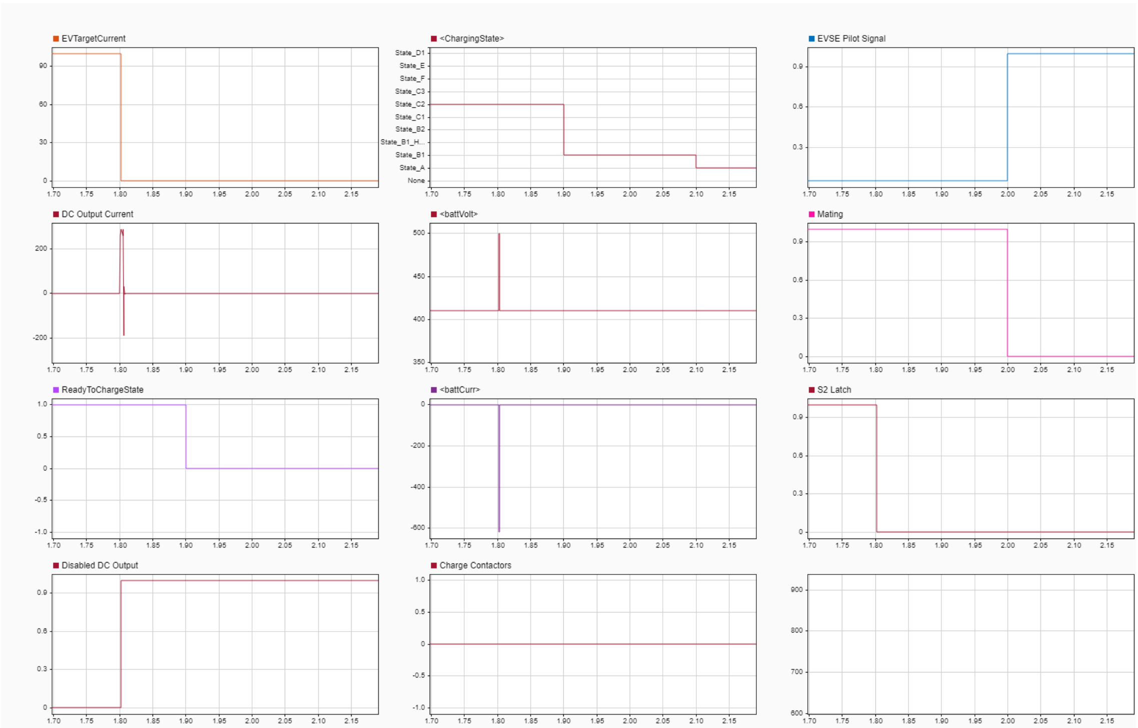


Figure 9.6: SAE Short Circuit Detection Before Energy Transfer Close Up

The figure 9.6 shows a short circuit occurring at 1.80 seconds before the energy transfer begins. In the following, there is step by step elaboration of the working process in parallel to the results seen the graph according to the standard EV initiated emergency shutdown sequence 8.2.

1. Within 1 ms of the short circuit detection, the EV Target Current i.e., target current communicated by the vehicle to the EVSE goes to zero, also the DC output is disabled and S2 Latch opens up with that.
2. The state C2 with in 10 ms goes to B1, which changes the ReadyToChargeState to false.

3. Within another 10 ms of time, the EVSE Pilot Signal goes to 1, and with un-mating at that instant, within another 100 ms the state changes to ’A’.

During Energy Transfer

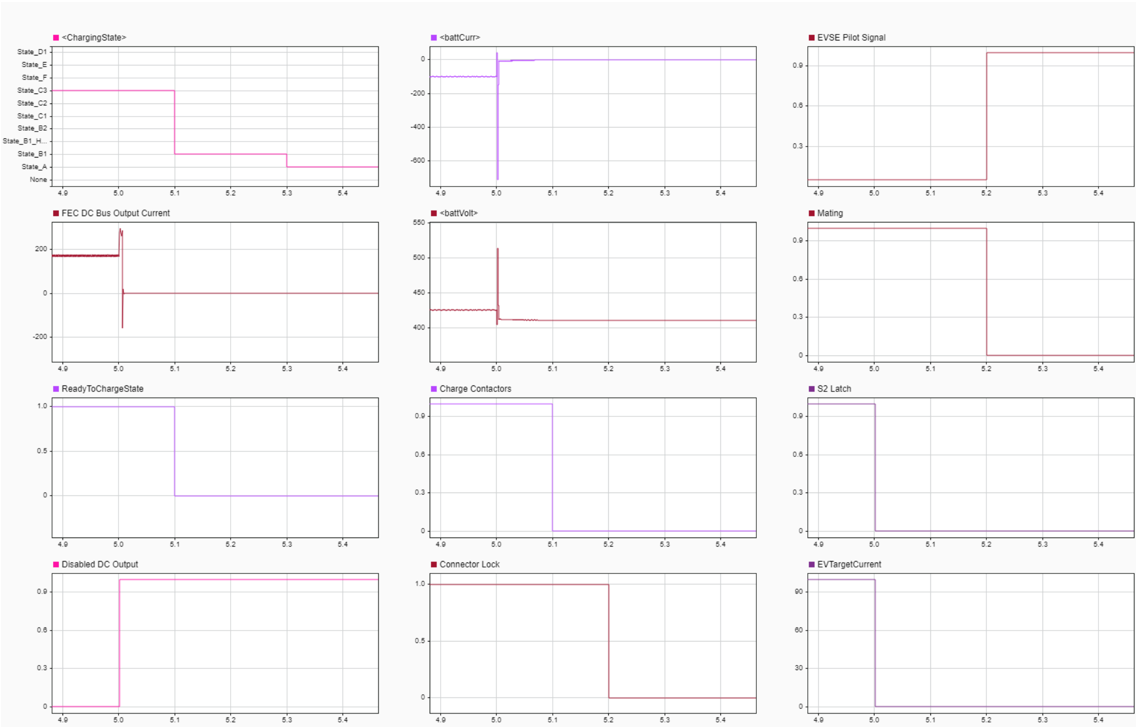


Figure 9.7: SAE Short Circuit Detection During Energy Transfer Close Up

Figure 9.7 indicates the short circuit fault occurring at 5 second time stop i.e., during the energy transfer, the following points highlight the shutdown after the detection.

- Within 1 ms of delay, short circuit is detected and DC Output is disabled actively and S2 Latch is opened and EVTargetCurrent goes to zero from 100A, as per the standard step by step approach.
- As could be seen that the battery current dips to a magnitude higher than that of the short circuit before the energy transfer and same could be said for the voltage spike.
- When the battery voltage and current stablizes and further within 100 ms of duration, the charge contactors are open when the welding detection response is sent by the EVSE to the EV and the EV ReadyToChargeState of the battery changes to false with the state going from ’C’ to ’B’.

- Within further 100 ms i.e., at 5.2 seconds, the Oscillator turns off by chaging the duty cycle to 100% and simultanuously the connector lock is open and then the un-mating occurs with the condition when the session stop response is sent by the EVSE to the EV and the connector lock is open. Doing so, the EVSE reaches stability within 100 ms and the CP changes the state to 'A' ending the shutdown process.

9.2.3 Analysis

The following points explain how the FEC, DC-DC Converter and Battery components react to the short circuit scenarios before and during the energy transfer in a DC Fast Charging System.

1. **Before Energy Transfer Battery Current Dip:** As could be seen in the figures of the energy transfer before the energy transfer that battery current experiences a negative dip of around -600A magnitute. As the short circuit takes place, the first reaction of the battery is current reversal since the natural reaction of the system would be to discharge the energy through the short circuit path.
2. **Before Energy Transfer Battery Voltage Spike:** As soon as the short circuit is initiated, a low impedence path sudden creation makes the stored energy to be relocated rapidly, resulting in higher transient battery terminal voltage, the peak observed are proportional to the capactive and inductive components used throughout the circuit that is used as a resistance for such change in current.
3. **FEC DC Output Current:** The major purpose of FEC subsystem is to regulate and stabilize the output current and voltage within the requested range. When the short-circuit occurs, a 2 ms more or less duration of the instability appears as seen by the figures since it tries to maintain the required characteristics of the output current and voltage. This surge of current at FEC end is necessary to meet the sudden change due to the short circuit and it is directly related to the duration of the short circuit.
4. **Duration of the Battey Voltage, Current Peaks and FEC Parameters:** As seen the total duration of current dip and voltage peak for the high voltage battery is very minor as compared to that of the FEC output current and voltage, this is due to the fact that battery is not highly actively taking part in the transfer of energy before the energy transfer. FEC protection system on the other side takes some time to take action to reduce the current and voltage or isolating the system completely. Since FEC is controlling the power flow through the lines, the

waveform of the FEC current and voltage takes 2 ms more or less before it gains stability and the shutdown is initiated.

5. **Peaks and Dips Magnitude Increment during Energy Transfer:** As could be indicated through the energy transfer phase, higher energy is involved and also the battery is taking part within the energy flow path by accepting the current coming from the EVSE through coupler and cable. Henceforth, the stored energy with in the FEC and the flow path in to the battery concludes in larger magnitudes of dip and peaks during the fault occurance. Also, higher energy storage with in the inductive FEC, DC-DC converter and cable elements causes higher transient voltage spike during the energy transfer as soon as the fault occurs

6. **FEC Response before or during Energy Transfer:** During or before graphs indicate that the FEC behaviour is similar in some ways indicating that the FEC aims to stabilize the output parameters when the fault occurs either before or during the energy transfer in the same protective manner, resulting in similar behaviour i.e., stabilizing within 2 ms limiting the current and voltage. Multiple reasons could be associated to this, i.e., it could be because due to the inertia due to the energy flow, it is difficult to drop the current and voltage immediately to zero, resulting in increment at first place also because the system is working at a higher power levels hence critical transient behaviour observed. Also, the inductive elements such as the inductors used and transformer winding are used to oppose sudden or abrupt changes in the current, in order to make that change low as possible, a higher FEC DC output voltage transient is created. Finally, the capacitors in the system used are for better stability through transients, when fault occurs with a minor delay response time, the capacitive discharge of immediate energy could result in a problem for current and voltage spikes at FEC DC output.

9.2.4 Comparison

1. **Shutdown Procedure:** In IEC, the shutdown process is more gradual especially switching to different states, while in SAE the transition slightly rapid, with immediate responses from the ReadyToCharge, CP pilot and EV Status. The overall IEC shutdown process has slightly longer duration i.e., 500 ms, of fault detection to shutdown which emphasizes more on the accuracy of all working parameters and their coherence with each other while the SAE that has a duration of around 300 ms focuses more on the rapidness of detection and initiated of shutdown.

2. **Charging Process:** SAE focuses on as soon as possible halt of the charging as the fault is detected so to protect the EVSE components and battery of the

EV, hence lowering the fault length of occurrence. IEC focuses and emphasizes controlled shutdown where all the components functioning are intertwined and dependence onto one another which comes at a cost of slightly longer duration of shutdown.

3. A common thing to be observed is that both systems show similar spikes and dips which is because both systems uses same EVSE parameters, while the communication protocol and the standard specific shutdown is different i.e., hence the main feature to focus is how both the standards transitions from one state i.e., faulted to a more stable state in order to protect both the EV and EVSE.

9.3 Load Dump Results

For the load dump investigation scenario, two separate conditions were considered i.e., within the threshold battery voltage and one where the battery voltage spike is higher than the given range hence resulting in shutdown i.e., over-voltage condition.

9.3.1 IEC 61851

Within Threshold

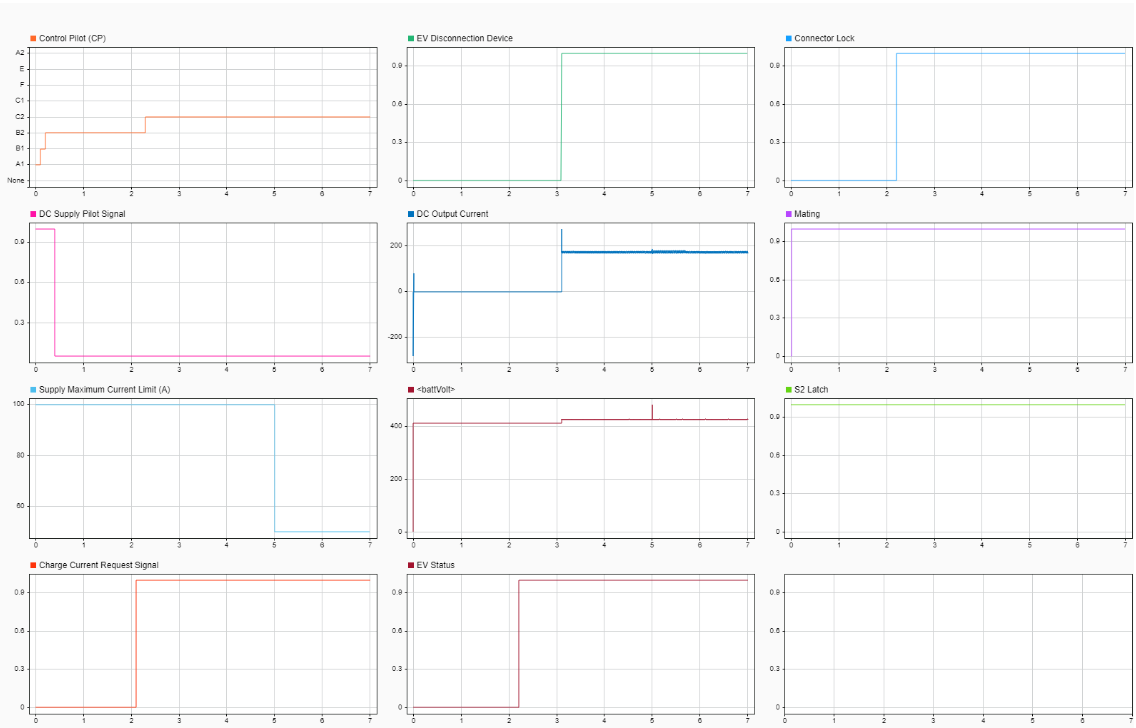


Figure 9.8: IEC Load Dump within Threshold

According to the IEC Standard, the load dump condition is more stringent and requires the voltage to be higher than 110% of the maximum voltage communicated by the EV during the chargediscovery session. So, to consider below threshold condition a 2 ms load dump is considered and shown in figure 9.8. A spike is observed for the battery voltage from 5 seconds time stop but since it is below the threshold, it continues to charge the battery afterwards with slight to no effect to other parameters mainly due to the voltage damper circuit applied around the DC+ line.

Above Threshold

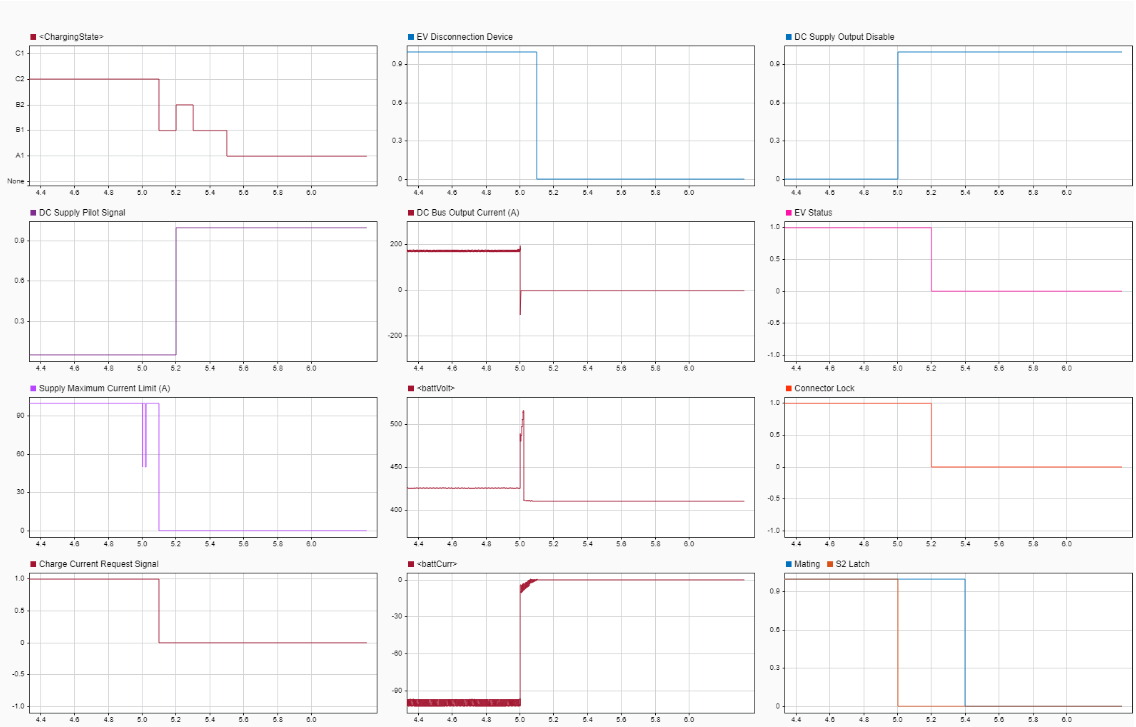


Figure 9.9: IEC Load Dump above Threshold Detection

Considering the above the threshold case, a 20 ms load dump is considered at 5 second time stop, hence the following is the analysis of the results in figure 9.9

- As soon as the load dump is initiated at 5th second, a continuous monitoring is made to see when it goes above the 110% of the maximum voltage and when it does, the EVSE initiate the emergency shut down which is similar to the one explained previously.
- With the detection, the latch S2 opens and the DC supply output is disabled and due to this the battery current rushes to zero and similar concept applies to the battery voltage as well.
- With the state 'C2' going to state 'B1', the charge current request signal, maximum current supply limit and EV disconnection device goes to zero which stabilizes the battery current and voltage due to disconnection.
- At 5.2 second, the connector lock unlocks and EV status changes to false.
- And finally by un-mating at 5.4 second, the system state changes from 'B1' to 'A1'.

9.3.2 SAE J1772

Within Threshold

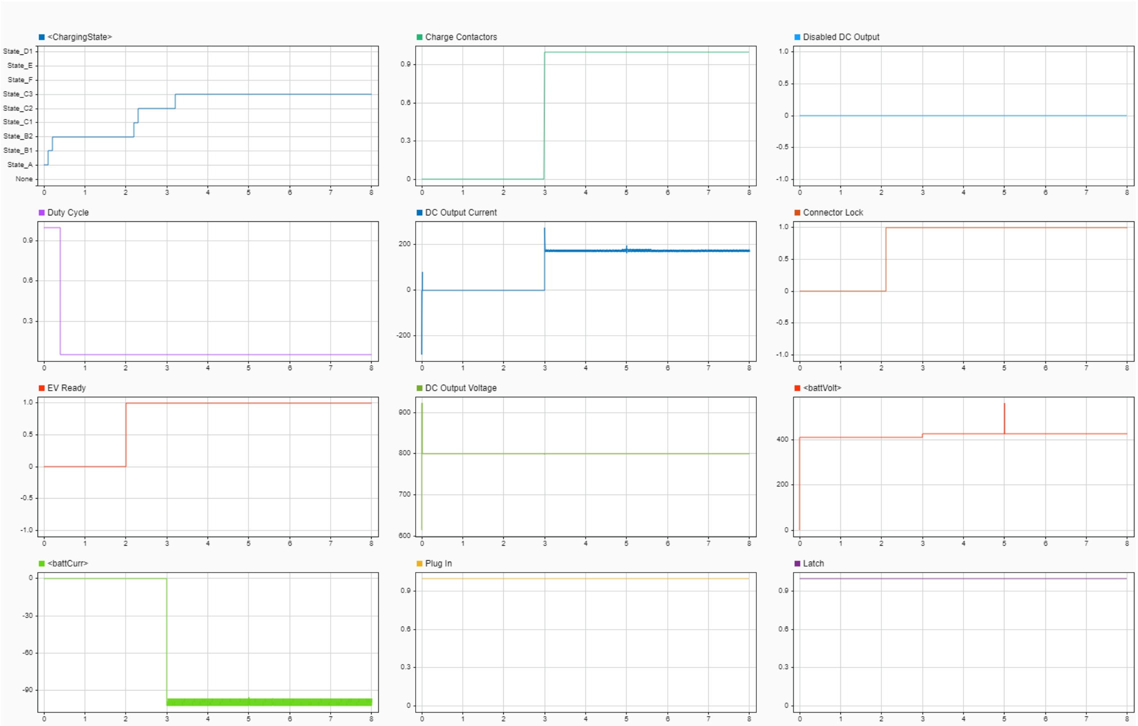


Figure 9.10: SAE Load Dump within Threshold

For SAE standard, the threshold mentioned for the EVSE initiated shutdown is 550V [29], which is less stringent than the IEC standard, hence considering a load dump for 5 ms results in a voltage spike is observed that is less than the threshold, which does not effect the charging process and it continues without any stoppage or shutdown. As it could be seen in figure 9.10 a spike is observed with battery voltage while the battery current seems to be unaffected due to the over-voltage damping circuit around the DC+ line. While considering the FEC DC output current, it seems to have slightly higher ripple since due to load dump it requires some time to stabilize with the feedback control circuit.

Above Threshold

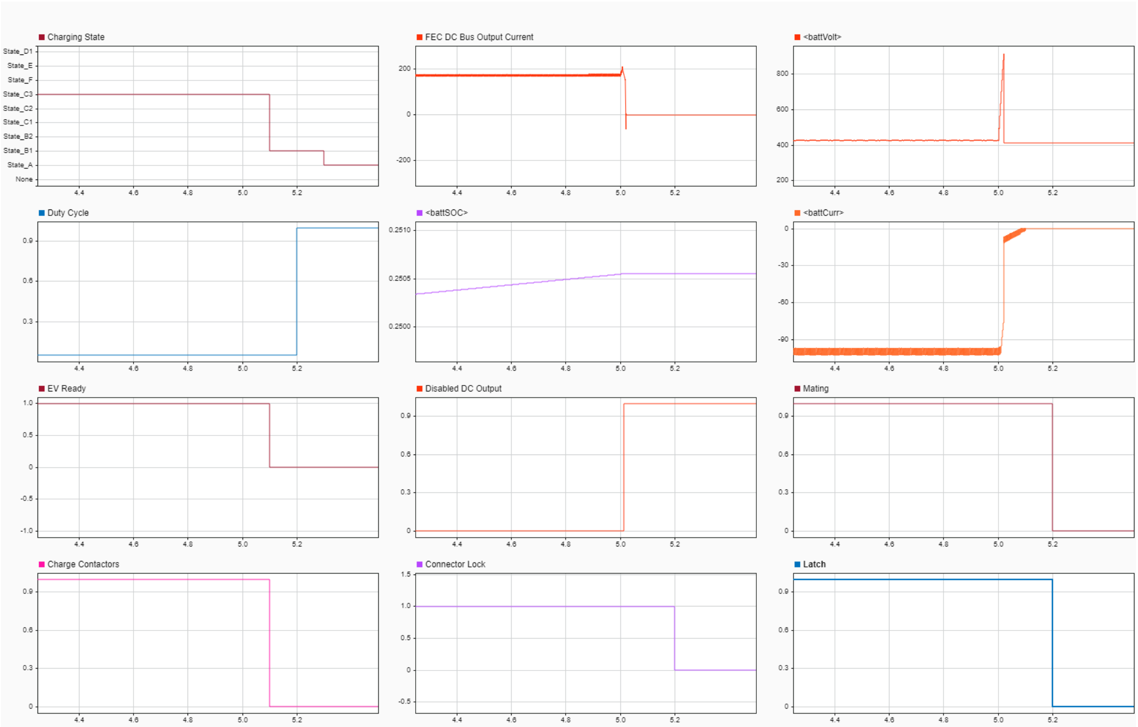


Figure 9.11: SAE Load Dump above Threshold Detection

A load dump duration of 20 ms was considered in order to simulate a scenario of exceeding the voltage limit of the battery and progressively going to the EVSE initiated emergency shutdown 8.3. The figure 9.11 shows that and following is the description associated to it.

- At 5.0 seconds the load dump is initiated at the battery ends that goes for around 20 ms. The threshold mentioned by the SAE standard [29] is 550V and as soon as that it is crossed for a continuity of 9 ms, the emergency shutdown is initiated.
- The first parameter controlled in this scene is to disable the DC output as soon as it goes above 9 ms.
- Next step is charge contactors opening and EV ready 'false' with the state changing from 'C3' to state 'B1' after 125 ms approximately.
- When the battery current stably goes to zero and battery voltage stabilize around it non-charging voltage, at 5.20 second i.e., 200 ms after the event, the connector lock opens with the duty cycle going to 100%.
- Un-mating results in changing the state from 'B1' to 'A'.

9.3.3 Analysis

1. **Voltage Spike:** Due to load dump i.e., battery abrupt disconnection results in the inductive parts releasing the energy into the system. And due to sudden dis-connectivity, the energy released results in voltage spike at the terminals of the battery.
2. **Influence on Battery Current:** During the load dump, the current at the battery terminals seems to be stable due to the presence of load dump dampers. Due to the detection of load dump and initiation of shutdown by the respective standards results in the current to abruptly lower down close to zero.
3. **Influence on FEC:** During the load dump, the FEC increased ripple can be observed, which is likely to be FEC understanding the situation by damping the voltage spike before the EVSE detects it and initiate the shutdown, but since the dampers used across the battery terminals, it has not a major affect on the current.

9.3.4 Comparison

1. **Duration of Shutdown:** Duration of Shutdown: IEC standard as commented before takes around 500 ms to 600 ms to change its state from C2 to A1 while SAE takes around 300 ms to detect the fault to changing state of CP to 'A', indicating that SAE depicts faster response time in disconnecting the battery from the EVSE so to minimize the damage that could occur to the components of both, while the IEC based model exposes the parts to such stress for slightly longer period but it also emphasizes on such shutdown to be well controlled and the parameters to be within the protective limits given by the standard.

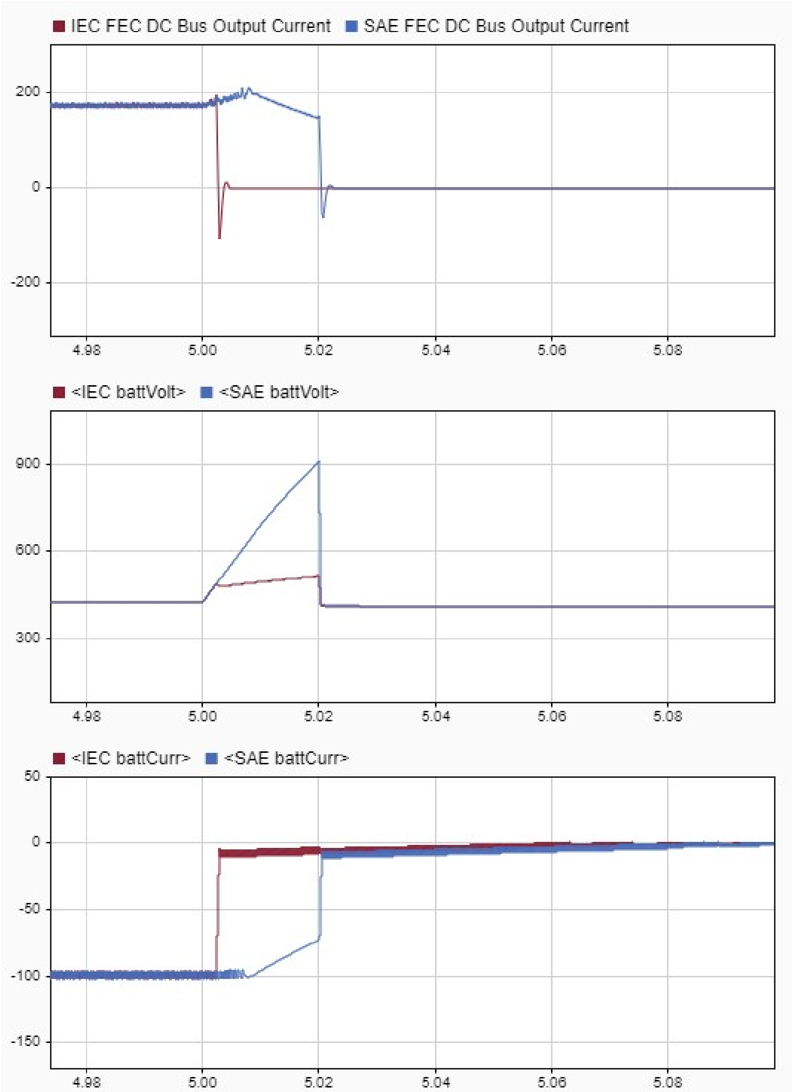


Figure 9.12: Comparison of the SAE and IEC based Shutdown during Load Dump Scenario

2. **FEC Current Behaviour:** As the figure 9.12 suggests that the blue indicating SAE based shows a ripple affect increasing to a certain period i.e., before it stabilizes to zero at around 5.02 second, while for IEC based model, the stringent condition causes the current to drop as soon as 110% of the maximum voltage is reached hence it stabilizes faster when compared with SAE.

3. **Battery Voltage:** For SAE, the voltage peaks around 900V with quick drop to zero while for IEC the peak is fairly lower since it damps the voltage more quickly SAE waits for 9 ms to verify the condition before damping it.

4. **Battery Current:** The current response in the IEC is faster since it does not has

a threshold of 9 ms before the DC disables hence it goes rapidly to stabilize around zero when DC disables, while for SAE it takes some time due it DC disabling later due to threshold limits.

10 Conclusion

10.1 Near To The Future Advancements

10.1.1 Today's Challenges and Tomorrow's Solutions

The adoption of EVs throughout the globe in an effort to reduce global emission and step into a more Eco-friendly technology for the road transportation has come up with a lot of benefits that regions around the globe are adopting to, but it does come up at a cost especially when different countries accept to adopt different standards. In order to increase the acceptance of EV adoption worldwide, it is necessary to work on harmonization, the differences of two major standards adopted i.e., IEC and SAE based standards do link together but have substantial differences that are to be focused at.

The main differential focus is the usage of connectors, communication standards, and safety protocols for the two major EV using regions i.e., EU and USA, leading to a more universal based EV models and charging infrastructure such as usage of CCS type 2 charger in EU and CCS type 1 charger in USA, that could potentially lead to some compatibility issues when it comes to harmonization. On the other part of the story, the safety aspect is also considered as a diverging pivot for the two standards and how they react when a fault is considered such as short circuit and load dump as it was considered in the studies. Hence both the standards charging process differentiate at a certain amount that are considered at the moment when OEMs develop the EVs and when the charging infrastructure deployment is considered in different regions, resulting in higher complexity, uniqueness and ultimately cost.

With the adoption of EV increasing, in order to decrease EV range anxiety and increase EV range, higher power density, energy density and low self-discharge rate with extended life and without memory effect Li-Ion Batteries are being adopted, which increases the potential of thermal instability directly linked to exothermic reaction that can be triggered either during charging or discharging [57, 43, 40, 45, 44]. According to the research [68], EV fire incidents have not been stored since the acceptance of it, with different level of severity, and around 52% of the incident probability was due to the internal short circuit, while external short circuit posed around 26% of the accident probability, hence it could be considered that short circuit plays a crucial role in majority of the EV failures [1].

The interest of this research lies in creating step by step DC Fast Charging Model starting from basic idea of charging a battery and ending it with IEC and SAE based standard models that not only considers high voltage batteries currently used in the vehicles but also communication protocols that both the standards use in order to create a sense of software and hardware based connection in their respective regions to charge vehicle. And with this adoption, the charging structure and EV battery were put to test considering short circuit and load dump conditions that are statistically more prone to occur. As it is known that EV battery abuse can not be avoided that could be due to mechanical damage, battery leak, over-charge, and discharge [53] and which can directly or indirectly lead to unavoidable short circuit scenario or even load dump condition when battery is disconnected while the EV load still connected to the charging structure during charging, hence causing damage to the battery due to overheating and it is also observed that majorly thermal runaway is caused by short circuit leading ultimately to fire or even the worst case scenario is explosion [19, 38]. With these Matlab based models working on respective standards and communication protocols can be further studied and research with increased complexity in order to mimic different fault conditions that could potentially decrease EV longevity and cost damage to high priced components of EVSE. It also provide advantage in understanding the faulted conditions on an academic level to help understand how different standards react to different scenarios and how it could effect the batteries and EVSE. Also, it could be put into research for optimization procedures, i.e., to adopt different strategies in order to react in a more accurate manner to even more severe scenarios that in today's time would result in major damage to the EV or even EVSE.

One of the solution in order to reduce complexity and cost is the adoption of a well more harmonized standard in order to create a more global charging network, also more advanced electronics and communication standards that would reduce the accidental probability by optimizing the start up, charging and shutdown procedure in case of fault detection without performance compromise.

10.1.2 Mega-Watt Charging System

With talks going on now for the wide acceptance of heavy duty electric vehicles and the key elements that are considered is higher range with fast charging times. MCS offered by CharIN [63] takes these things in to thinking i.e., charge rate essential for the widespread adoption of battery in HDV increasing the driving range per minute spent charging and also even higher level and faster communication reducing the failed charging event downtime. The communication itself uses the power line communication (PLC) with HomePlug GreenPHY communication protocol and CharIN [63] recommends the usage of ISO 15118-20 communication protocol developed in 2022 i.e., highest level of protection and security as compared to SAE and DIN protocols. And since it adopts a charging pattern that can transfer 6x more current with 10x more power as compared to CCS charger used in DC fast charging for LDV charging. With the adoption of MCS, short circuit condition has also been considered. MCS by CharIN mainly adopts the IEC 61851, IEC 62196 and UL for the charging, cabling, safety and thermal aspects.

In the simulation world, the developed model within this research poses an advantage for the on-going development of Megawatt charging system during the early phases and also during its implementation in real world scenarios i.e., modelling a larger capacity battery used in heavy duty vehicles and with the standardized approach depending on the region i.e., EU, USA or any other region with their respective standard applied to the model developed, simulation testing could be done to detect discrepancies and faults conditions.

Since, MCS considers high voltage of 500-1250 VDC and maximum continuous rating of 3000 ADC testing as per the CharIN [63], resulting in large amount of power transfer to cut down charging time of long range high capacity batteries, fault risks especially short circuit, load dump and finally resulting in thermal runaway is increased. By modifying the model for creating different charging scenarios for the MCS case, it could be used for research purpose to study the risks that could occur and possibility of handling those faults in a more secure manner since it deals with a magnitude of 6x more current that is being used in a normal DC Fast Charging System. Since, MCS according to CharIN uses IEC protocol for most it's aspect, it is necessary to follow a path with respect to IEC standard and identifying where and when modifications and improvements can be brought about with in the protocol in order to manage megawatt of power and fault conditions occurring within the system so to research if higher power transition does not pose any further complex problem. Also, scalability is a factor that needs to be considered, i.e., with the models developed, state flow of new communication protocol model can be developed, modifications to the standard state flow can be made to consider the increased power and different battery technologies and advancements can be put to test within the simulation domain. Finally, considering the increased cost, the batteries and the EVSE may have due to the reasons mentioned above, it is highly recommended to consider testing the MCS normal and faulted testing conditions on the simulink prototypes which of course increases the virtual testing burden yet it could cut down the cost before the development phase to a greater extent, with simulations, better and detailed insights could be seen which are difficult to obtain while being in a real world scenario at a cost of less reality based modelling, which when developed could be fine tuned depending on the surrounding conditions.

10.2 Brief Summary

Finally, the research concludes with a brief and precise summary of what has been done within this paper as following:

- First part focused on a theoretical based study, in which the charging standard used with in Europe and USA was studied, in which their charging start up sequence was studied how they would effect the charging process i.e., the effect on efficiency, user experience, infrastructural demand and safety.
- A comparison was made between the two DC Fast Charging Standards highlighting their key features, similarities and differences and of course their effect on charging process.
- Theoretical based study was made of DC output current and voltage ripple, Short Circuit Testing and Load Dump Conditions according to the standards and a comparison was made between the two.
- Moving on to a practical and simulation approach, a simple DC Fast Charging Model, a high voltage battery model and their integration was developed, along with battery testing was performed. Then, finally a communication based model with standards i.e., IEC and SAE was considered and then integrated with the electrical based model previously considered.
- As the last part of the research, the theoretical based study of different fault conditions i.e., short circuit and load dump was put to test considering the two standards, by developing shutdown sequence that both the standards follow when meeting with the worst case scenarios and comparing them.

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