Rapid EV Chargers: Implementation of a Charger

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EEA Conference & Exhibition 2016, 22 - 24 June, Wellington

Abstract

The uptake of electric vehicles in New Zealand is rapidly increasing and there is a desire for information about charging systems. This information is required by consumers, engineers, and businesses interested in installing charging infrastructure. This project was completed during the 2015-2016 summer break and aimed to enhance the University of Canterbury EPECentre's knowledge of charging technologies. In addition to gaining a general understanding of charging technologies, detailed research into rapid DC chargers using the CHAdeMO protocol was conducted. The project also included the building and testing of an open source 12kW rapid DC charger using the CHAdeMO protocol. This paper combines the findings of researching the numerous charging technologies with the practical experience of building the charger. Although the charger was not tested with a compatible car due to time constraints, it was successfully built and initial testing was completed. Plans are also underway to conduct more comprehensive testing on the charger to fully characterise it.

1 Introduction

During the university summer break of 2015-2016 a summer scholarship was awarded to the author to work on an open source rapid electric charger (EV). The primary purpose of this project was to gain an understanding of rapid EV charging systems; in particular, chargers using the CHAdeMO protocol. The University of Canterbury wanted to gain further understanding of the technology used in these chargers for research and teaching purposes. The eventual aim is to research how to use the chargers to allow bidirectional power flow for vehicle-to-grid (V2G) applications. A practical component of the project was required with the build and test of an open source charger.

As of March 31st 2016, there are 1128 light EVs registered in New Zealand with this number rapidly increasing [1]. As EVs become more mainstream within New Zealand, the demand for charging technologies will substantially increase. This includes both residential systems and commercial public chargers. In particular, there will be a demand for rapid charging stations where consumers will be able to recharge their vehicles to approximately 80% in as little as 30 minutes. This will help reduce 'range anxiety' and further encourage consumers to use their EVs for longer journeys. To encourage the uptake of these technologies, stakeholders including consumers, investors, engineers, and electricity companies will need reliable information. Although there is plenty of information available, it is challenging to combine numerous sources and determine how it relates to the New Zealand market. As part the summer project, significant research into EV charger technology with an emphasis on CHAdeMO chargers was completed. This paper combines the research into EV charging technologies with the experiences of building the open source CHAdeMO charger to provide a source of information for anyone interested this rapidly changing field.

2 Electric Vehicle Charging Technologies

The field of electric vehicle (EV) charging systems is rapidly evolving with numerous standards, types, connectors, and terms used to describe chargers. The generic term used to describe the piece of equipment used to charge an electric vehicle is 'electric vehicle supply equipment' (EVSE). EVSE can be further categorised into three levels that relate to their output power capabilities [2]. Level 1 and level 2 EVSE both supply alternating current (AC) to an electric vehicle's on-board charger and level 3 systems supply direct current (DC) to the EV [2]. The use of the term 'charger' for levels 1 and 2 is misleading, as they are not technically chargers. They supply AC electricity to the EV where the on-board charger converts the AC to DC, which charges the batteries [2]. EVSE also provides important safety features for both users and charging equipment [3].

The battery management system (BMS) is another vital component in an EV charging system. It is responsible for thermal management, cell balancing, over charge and over discharge monitoring of the battery pack [4]. An EV battery pack is not made of a single battery; instead, many individual cells are combined to form a bank [4]. A single cell may only have a small safe working voltage range and it is important to ensure it stays within this range. This is particularly important with variants of lithium ion batteries commonly used in EVs. Over charge and over discharge can result in disastrous consequences including reduced battery life or total battery failure causing fires [4]. It is the job of the BMS to monitor the battery cells to ensure they *all* stay within normal operating voltages and temperatures [4]. The BMS also balances individual cells by redistributing charge from cells of higher electric potential (voltage) to lower potential cells [4]. BMS's use numerous techniques to manage the battery pack and Cao et al. (2008) give an excellent review of such technology [5]. The BMS is also responsible for the voltage and current requests from the charger [6] . This includes both the on board charger for levels 1 and 2 or the off board charger for level 3 EVSE. Multiple charging profiles (constant current, constant voltage etc.) are available to charge a battery; however, this is outside the scope of this paper.

2.1 Level 1 and 2 Charging

As previously, mentioned, level 1 and 2 chargers provide AC electricity to the EV's on board charger. There is communication between the EVSE and the EV to ensure the on board charger does not draw more current than the EVSE can supply, and to safely protect the user and equipment [3]. The current limit is dependent on the EVSE level and more importantly, its electrical supply.

Level 1 chargers are typically inline chargers which are stored with the EV. Their compatibility with standard household electrical sockets limits the power they can deliver which consequently increases charging times. This portability, combined with their compatibly, allows their use as emergency chargers in situations where the EV battery has gone flat. In the United States, level 1 supplies correspond to a single phase supply of 12A at 110V. This allows a maximum power transfer to the EV of 1.4 kW. These chargers are slow and it can typically take 4-11 hours to fully charge an EV [2]. In countries such as New Zealand, where the grid voltage is 230V single phase, this allows a higher charging power for the same current, which reduces charging times. Assuming people's use of their EVs does not drain the battery too much on a daily basis, a level 1 EVSE can provide adequate charging overnight. Figure 1 shows an example level 1 EVSE.

Level 2 EVSE aims to improve the power output by using a dedicated 'box' permanently mounted on a wall or other appropriate structure. The permanently mounted box allows for a dedicated electrical supply of sufficient capacity, enabling a significantly higher power output compared to level 1. In the United States, the electrical supply to the EVSE is often spilt phase. This increases the voltage supplied to the EV to 240V, which significantly increases the power without drawing more current. Level 2 EVSE can provide between 4 and 20 kW depending on the local supply. This can reduce charging times of an EV to 1-6 hours. Both homes and dedicated charging facilities (private or public) are common locations for level 2 EVSE. Figure 2 shows an example level 2 EVSE.

Figure 1: A level 1 EVSE.[1]

Figure 2: A level 2 EVSE.[2]

The standardisation of connectors and protocols for levels 1 and 2 is variable across countries and manufacturers. In America, the Society of Automotive Engineers' (SAE) J1772 standard is used to define the connector and the protocol used for levels 1 and 2 EVSE. Figure 3 shows an example SAE J1772 charge port. The connector used in Europe for levels 1 and 2 charging is the IEC 62196-2 or Mennekes connector and is shown in Figure 4. To confuse matters further, The IEC 62196 standard also defines the J1772 connector as the type 1 connector with the Mennekes connector defined as type 2. The type of connector does not relate to the EVSE level. It is important to note that both connectors use the same signalling protocol for controlling the charging process. Although both connectors are similar, the type 2 connector has two additional power pins. This is to allow a three phase AC supply to be connected directly to the EVs on board charger, further reducing charge time. Given J1772 and type 2 connectors use the same protocols, it is possible to purchase adapters to swap between connector types. Table 1 lists example manufacturers who use each of the connectors.

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[1] Retrieved from: http://www.roperld.com/Science/EVChargingSWVA_SWV.htm

[2] Retrieved from: https://www.emotorwerks.com/store-juicebox-ev-charging-stations/202-juicebox-pro-40-smart-40-amp-evse-with-24-foot-cable

Figure 3: J1772 connector and charge port.[3]

Figure 4: Mennekes Connector. Also known as Type 2 and 62196-2.[4]

Table 1: Manufacturers who use J1772 and 62196-2

Manufacturer	Vehicle	Connector
Nissan	Leaf	J1772
Mitsubishi	i-MiEV	J1772 (American Models 62196-2 (European Models)
BMW	i3	62196-2
Ford	Focus	J1772

Level 1 and level 2 EVSE with either the J1772 or type 2 connector contain signalling electronics to improve user safety and protect the infrastructure. Figure 5 contains an example of the J1772 electronic circuit schematic. One of the key safety features with the signalling electronics is the prevention of voltage being present at the connector terminals while it is not correctly mated to the EV [7]. This helps protect the user, by ensuring if they were to touch the connector pins they would not receive an electric shock. While the connector is connected, the vehicle is also immobilised to prevent driving while charging [7]. The EVSE also monitors the potential ground to ensure there is no earth leakage, further reducing electric shock risk [7]. Communications between the EVSE and EV are not bidirectional and are completed using a modulated 1 kHz square wave [7]. The EVSE generates the square wave and its duty cycle indicates to the EV the maximum available current. The square wave nominally oscillates between -12V and +12V, however, this voltage can also be altered to indicate various states. These states are: not connected; EV connected; EV charge; EV charge ventilation required; and error [7]. Further information is available on the OpenEVSE website.[5]

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[3] Retrieved from: http://www.edn.com/electronics-blogs/automotive-currents/4421241/How-the-J1772-charging-standard-for-plug-in-vehicles-works

[4] Retrieved from: http://www.mennekes.de/es/latest0.html?tx_ttnews%5Btt_news%5D=47&cHash=2cbd3681e707bf1d7049bf520c120e95

[5] http://support.openevse.com/support/home

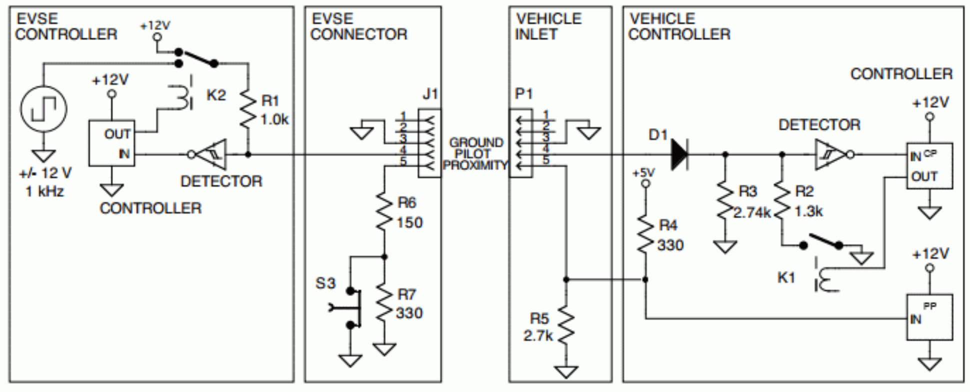

Figure 5: Signalling circuit schematic for the J1772 standard.[6]

2.2 DC Rapid Charging

Level 3 is the highest power level for EV charging systems. DC charging, fast charging or rapid charging are other common names used to refer to level 3 EVSE. Due to their large power requirements and significant capital cost, level 3 systems are found only at dedicated charging facilities [8]. The two major competing standards for level 3 charging are the SAE combined charging system (CCS) and the Japanese CHAdeMO standard. The third standard is Tesla Motors' own Supercharger, which is only compatible with their vehicles. The Tesla Supercharger (Figure 7) is currently the world's fastest EV charger with 120kW installations found around the world [9]. Charging of Tesla vehicles using CHAdeMO infrastructure is also possible with the addition of an adapter produced by Tesla Motors. Unlike levels 1 and 2 EVSE, DC electricity is supplied to the EV, bypassing the on board charger. The charger is actually located off board and is the charging station. In the simplest terms, a level 3 EVSE is a controllable DC power supply. As with levels 1 and 2 systems, the BMS monitors the battery to ensure it stays within the safe operating parameter.

Figure 6: An example of a DC charger.[7]

Figure 7: A Tesla Motors Supercharger.[8]

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[6] Retrieved from: https://commons.wikimedia.org/w/index.php?curid=19090771

[7] Retrieved from: https://smartenergyacademy.psu.edu/gridstar/rapid-dc-electric-vehicle-charging

[8] Retrieved from: https://chargedevs.com/newswire/teslas-liquid-cooled-supercharger-cable-could-enable-faster-charge-times/

2.2.1 Combined Charging System (CCS)

CCS, also known colloquially as the combo standard, is an addition to the J1772 standard used for levels 1 and 2 AC charging. The combo plug uses the existing J1772 connector and adds two DC power pins to its base. This forms a connector known as a type 1 CCS connector. There is also a type 2 CCS connector, which is the addition of two DC power pins to the Mennekes connector used in Europe for AC charging. Figure 8 shows both types of connector and plug. The communications protocol used for CSS is the HomePlug standard for power line communications (PLC) [10]. Although HomePlug or PLC is not common for automotive communications, it is often used in smart grid applications [11]. High power EV chargers will become a significant load on electrical grids and their compatibility with smart gird protocols is advantageous. CCS infrastructure is commonly 50kW, however, the standard is likely to increase in the future [10]. Numerous manufacturers produce charging systems that comply with the SAE CCS standard.

Figure 8: Combined changing standard connectors and plugs. European version on the left (Type 2) and American version on the right (Type 1).[9]

2.2.2 CHAdeMO Protocol

The CHAdeMO association's name is a contraction of the French term 'charge de move', or "let's charge and move", and is short for the Japanese term "let's have some tea", indicating that CHAdeMO intends to provide rapid charging infrastructure so EV owners can recharge their vehicle in as little time as it takes to have a cup of tea. In general rapid chargers aim to charge the batteries to 80% capacity as charging times from 80% - 100% increase significantly due to a decrease in the current the batteries can take. A safety first design has been CHAdeMO's strength; with manufacturers required to have their chargers approved and tested by CHAdeMO before they are allowed to be marketed as official chargers. The CHAdeMO protocol uses a dedicated connector designed only for DC rapid charging. This enables EV manufacturers extra flexibility in positioning charge ports on their vehicles. The CHAdeMO protocol also has the capability of allowing bidirectional power flow or V2G. In some situations, the term vehicle-to-home (V2H) or vehicle-to-business (V2B) is preferred. This

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[9] Retrieved from: http://articles.sae.org/11484/

feature spawned out of a need for emergency power supplies after the March 2011 earthquake and subsequent Tsunami in Japan. Currently, very few products on the market utilise these features. Unsurprisingly, the CHAdeMO protocol is favoured among Japanese manufacturers, particularly Nissan and Mitsubishi who were part of the initial formation of the association. This information was sourced from the CHAdeMO Association's webpage [12].

For a more detail and technical description of the CHAdeMO protocol, please refer to the appendix.

3 Summer Work

eMotorWerks is a producer and retailer of EVSE based in the United States of America. They produce a range of products including level 2 EVSE, DC chargers and CHAdeMO controllers. Certain products within their range also come either as an assembled production unit or as a kitset for the 'DIY' user. On behalf of Northpower, the University of Canterbury purchased the following from eMotorWerks: an assembled 12kW smart charger, a kitset 12kW smart charger, a CHAdeMO controller, and a charging cable with CHAdeMO compatible 3D printed connector. Purchasing of the assembled charger was to assist in the construction of the kit charger. The open source design of the smart charger was a key reason for choosing eMotorWerks.

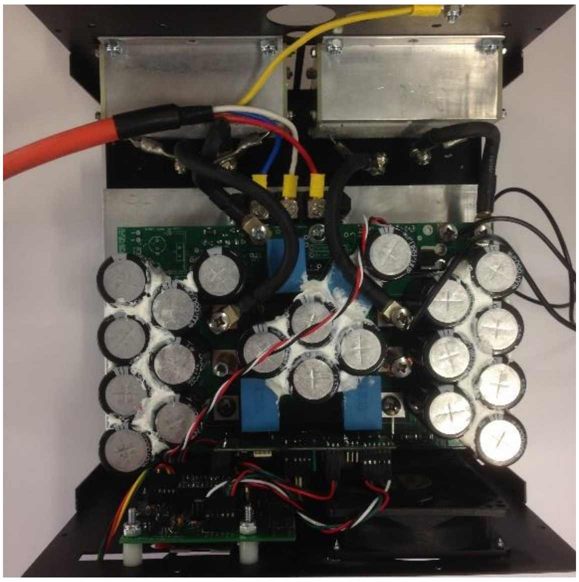


Figure 9: The assembled 12 kW DC charger.

Figure 10: The CHAdeMO Controller.

Figure 11: The 3D printed CHAdeMO connector from eMotorWerks.

3.1 Design and Construction

The 12kW smart charger is of a cascaded boost-buck topology. The charger is a standalone unit that can charge batteries with a range of parameters including voltage and battery capacity. In the simplest terms, the charger is a controllable DC power supply with both voltage and current mode control available. It also has functionality to communicate with a BMS to provide smarter charging protocols for battery packs with larger cell numbers. Furthermore, combining the smart charger with an eMotorWerks' CHAdeMO controller will produce a rapid DC EV charger that uses their version of the CHAdeMO protocol.

Both the first, boost stage and the second, buck stage use insulated-gate bipolar transistors (IGBTs) as the switching devices. Control for each IGBT is independent from one another, with a dedicated power factor correction (PFC) chip controlling the first stage and an Arduino microcontroller controlling the second stage. The PFC control chip uses a fixed PWM frequency of 22 kHz and maintains a power factor of better than 0.9 at the input. The charger design allows the user to configure the hardware to be compatible with a range of supply voltages, and output voltages and currents. The chargers were configured to work with a 3-phase 400V (phase-to-phase) input voltage. The DC bus voltage between the stages is also configurable and was set to 647 Vdc. Selection of this voltage was as per eMotorWerks recommendation to ensure compatibility with the CHAdeMO controller and New Zealand's electrical supply. The Arduino controlled buck stage uses the DC bus voltage to generate the desired DC output voltage. The charger has the ability to provide either a constant current or a constant voltage output.

The charger arrived with three printed circuit boards (PCB), two of which required complete assembly (power and control), and one required configuration and bug fixes (driver). Table 2 contains further information about what each board does and its key components. Although assembling the boards should have been a straightforward process, poor documentation considerably slowed it down. In particular, the incomplete and out of date build manual coupled with out of date schematics and bill of material (BOM) information caused delays while clarifications were sought from eMotorWerks.

Table 2: Description of each PCB for the charger.

Board	Description
Power	This board contains all the power electronics to implement the boost and buck convertors. Key components include the electrolytic bulk capacitors, filtering capacitors, IGBTs, hall effect current sensor, and filtering capacitors.
Driver	This board handles producing the signals required to drive the gates on the IGBT. It also contains the PFC chip used to generate the duty cycle to control the boost stage.
Control board	This board contains the Arduino microcontroller used for both the user interface control and for controlling the output voltage. Key components include the microcontroller, display, buttons, and signal conditioning circuitry.

Apart from the three circuit boards, the charger also has the following components: the heat sink; thermistor; two inductors; a three-phase rectifier; three cooling fans; 12Vdc power supply; and the metal enclosure. The heat sink is a 10mm thick aluminium plate with 60mm long fins to keep the IGBTs and three-phase rectifier within their operating temperatures. Bolts mount the IGBTs and rectifier to the heat sink and a thin layer of thermal paste between the component and heat sink enhances the thermal conduction between the surfaces. Silicone glued the thermistor onto the heat sink so the Arduino could monitor the temperature and ensure the IGBTs and rectifier stayed within operating temperatures; the system can de-rate the power output in situations where the heat sink temperature increases above a certain threshold. The inductors used as part of the boost and buck stages of the charger appear to be of a custom design as they had few manufacturer markings and did not appear to have a datasheet. Bolts mounted the inductors to the metal enclosure and jumper wires connected them to the power board. The rectifier is a standard four-diode bridge and worked with a range of inputs including single phase AC, three phase AC, and DC. Three standard 12Vdc computer fans provid additional airflow to cool the heat sink and other components, such as the electrolytic capacitors. The metal enclosure is not a required part, but it certainly made the assembly easier as it provided mounting points for the fans, and the rest of the components. The control board, driver board and cooling fans use the 12Vdc power adapter supplied by eMotorWerks. Figure 12 shows the completed charger.

Figure 12: The assembled charger.

Given the dangerous voltages present with the chargers, it was important to ensure user safety. Unfortunately, the chargers do not use an isolated design. Nor do they have adequate earthing to comply with the New Zealand wiring regulations (AS/NZS 3000:2007). As such, when constructing the charger, all exposed metal components (the enclosure, component mounting bolts, and fan grills) were connected together and connected to the AC supply earth. This included removing paint from the enclosure to ensure an adequate electrical bond to the metallic case. A bolt was used as the main earth point as per the New Zealand wiring regulations.

4 Results

The major aims of the project were to gain an understanding of CHAdeMO EV chargers and associated technologies, and to build and test an open source CHAdeMO EV charger. The author now has a significant understanding the CHAdeMO protocol, other EV charging protocols, and the electrical design of various chargers, fulfilling the first aim of the project. Building and testing of the open source CHAdeMO charger was mostly successful. Assembly of the kitset charger along with the testing procedures outlined by the manufacturer were completed. Unfortunately, without access to a compatible EV, with willing owner, such as a Nissan Leaf, complete testing of the CHAdeMO charger was not possible.

As this project was for a fixed duration (10 weeks), any delays encountered ultimately reduced the progress towards the end goal. Initially, shipping issues caused the first delays due to the packages arriving later than expected. As previously mentioned the lack of up-to-date documentation caused significant delays during the construction phase. Requested support from eMotorWerks was often a waiting game due to time zone differences and poor support processes. Other issues encountered included poor manufacturing of both the assembled charger and other components in the DIY kit. For example, bug fixes on the assembled charger were not completed. This was contradictory considering the chargers reportedly come tested from the manufacturer and are ready for use. Further examples of substandard manufacturing include poor soldering with dry joints and a surface mount capacitor shorted out due to a large solder blob.

Although the project was frustrating at times, the experience gained was immense. It was a fantastic opportunity to apply knowledge and skills acquired during the Electrical and Electronic Engineering Degree. In particular, the author's understanding of common power electronic topologies was enhanced and their surface mount soldering techniques also improved. The project also showed the importance of having correct documentation that is up to date, correct and easy to understand. The project also allowed the author to gain a significant understanding of EV charging technologies with a particular emphasis on rapid chargers using the CHAdeMO protocol.

5 Discussion and Conclusion

Testing of the charger with compatible EVs is the next important step in the project. This involves taking the equipment up to Northpower and using their EVs as a test platform. The initial testing will be to ensure the charger can successfully charge an EV using the CHAdeMO protocol. Once this has been completed, several more specific tests will be conducted. Ideally, data of the following phenomenon would be useful: charge time; charge currents and voltages over time (charge profile); AC and DC side power quality; power factor; and CAN bus communications. This data could be used to gain further understanding of EV chargers and their impacts on the grid. Furthermore, this information can be used to continue progress on achieving bidirectional power flow for V2G applications. This is a major goal of the University of Canterbury and the EPECentre as it creates the opportunity to use EVs as emergency power supplies.

As shown, the field of EV charging technology is currently overwhelmed with numerous technologies, standards and connectors. It is not as simple as plugging an EV into a universal charger. It is important for key stakeholders such as engineers to understand this field so they can determine the correct infrastructure to be installed into New Zealand. Unfortunately, it is likely commercial charging stations will have to support multiple connectors and protocols for some time. The battle between standards, particularity in the rapid DC charging area, is set to continue while various manufacturers support multiple standards. People have compared this to the videotape battle of VHS vs Betamax.

6 Acknowledgement

The authors acknowledge the funding provided by the Ministry of Business Innovation and Employment, Transpower, the EEA and the University of Canterbury for the GREEN Grid project that has enabled this research to be carried out. They also acknowledge and thank Northpower for the purchase of the materials that enabled this project to be carried out, and thank Russell Watson for his assistance. They also acknowledge Edsel Villa and Ken Smart from the University of Canterbury Power Electronics and Machines laboratories for their assistance.

7 Appendix – The CHAdeMO Protocol

On the most basic level, a CHAdeMO charger is simply a controllable DC power source. The EV being charged requests a current of a certain magnitude or a specific voltage and the charger supplies this. A typical CHAdeMO charger is therefore likely to have similar major components. Those components are a rectifier, an isolation transformer, filtering components (AC and DC side), power factor correction (PFC) components, DC-DC converter, controllers, and ground fault interrupters [13]. Figure 13 provides an example block diagram [14].

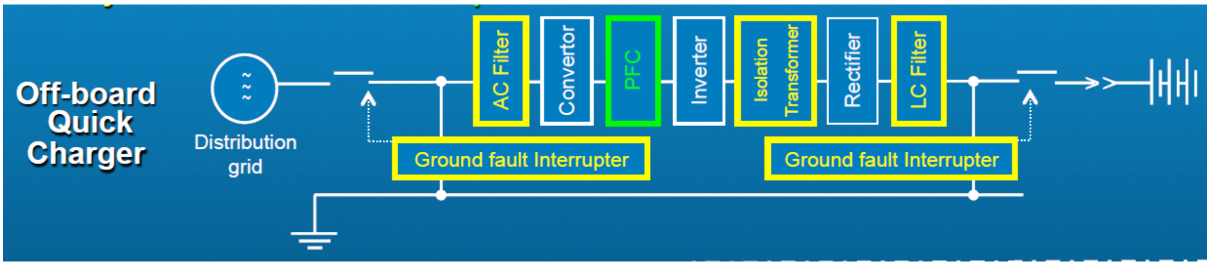


Figure 13: Block diagram of a typical CHAdeMO compatible charger.

The following section has been developed using information from the CHAdeMO Association’s website [12], and a paper [15] and presentation [14] by Anegawa.

The rectifier converts AC current to DC. Separation of the AC and DC ground with the use of an isolation transformer significantly improves the safety of the charger by preventing the injection of high voltage from the AC side into the battery system. The isolation stage is likely to be at a higher frequency than mains (50Hz or 60Hz) to reduce the cost and size of the transformer. AC side filtering helps to reduce harmonic distortion ensuring the charger complies with local regulations for power quality. The DC side filtering suppresses any AC ripple present within DC current supplied to the EV batteries, helping to reduce battery degradation. Since these chargers require large currents from the utility it is important to minimise reactive power and therefore a PFC stage is used. DC-DC conversion generally steps down the voltage from rectified supply to the level requested by the EV. Numerous topologies for this converter are available for manufacturers, each with their own benefits and drawbacks. The use of topologies such as the fly-back converter can also be advantageous as the converter itself provides galvanic isolation. This can reduce costs by removing the needs for a separate isolation transformer. A control system is required to regulate the DC voltage and current in order to charge the batteries safely and efficiently. Ground fault interrupters monitor the grounds (AC and DC side) for flowing ground current. In the event of detected ground currents, the charger is to prevent electric shock to the user and/or equipment damage.

As previously mentioned, the CHAdeMO association has adopted a safety first approach. The connector design and the CHAdeMO communication protocols are evidence of this. Figure 14 shows the connector layout indicating the DC power pins, five analogue pins, and two controller area network (CAN) bus pins. The analogue pins provide signals used to switch transistors as part of the analogue communications between the EV and charger. The two CAN bus pins provide the digital communications between the CV and charger. Figure 15 shows a flowchart explaining how the CHAdeMO protocol works and how the analogue signals are used [13].

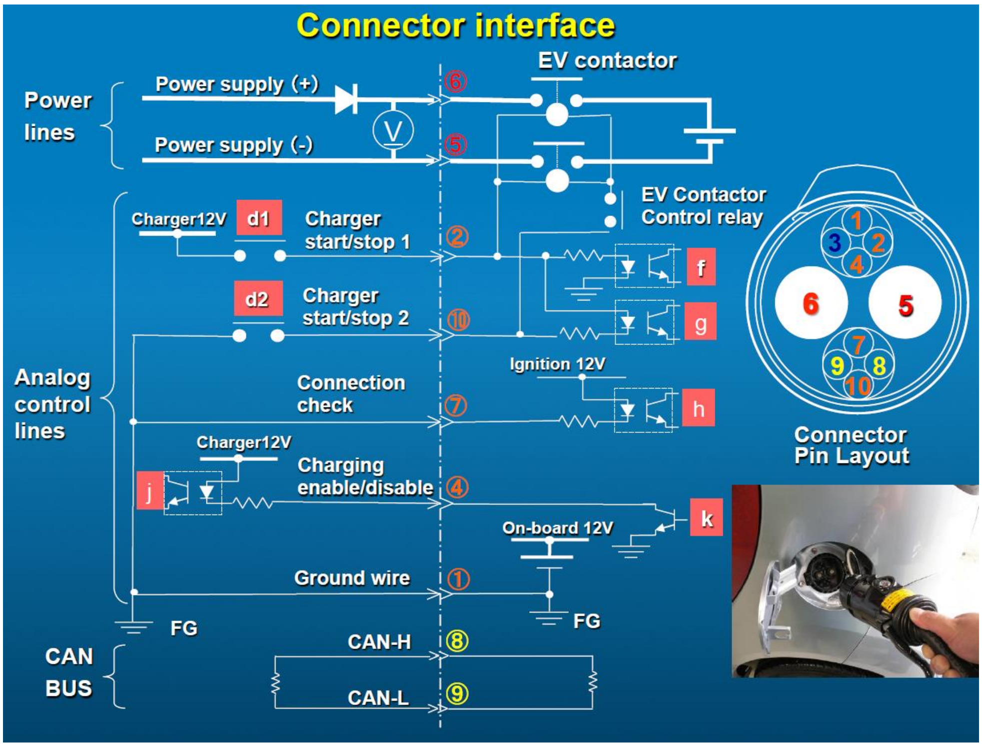
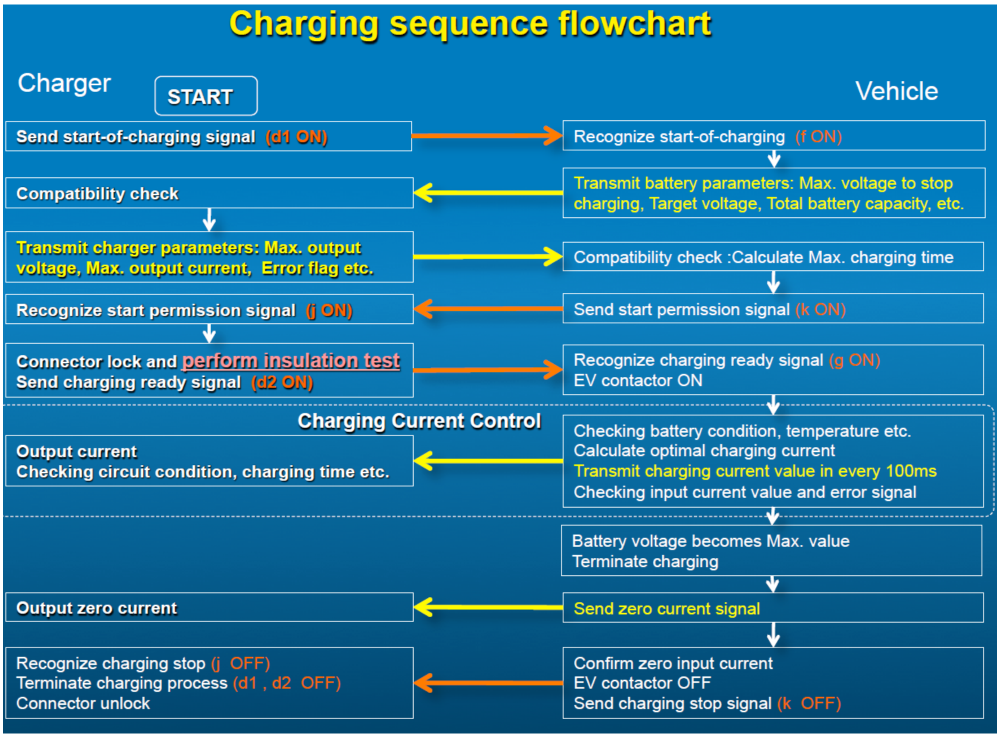


Figure 14: Description of the CHAdeMO connector pinout and schematic.



Charging sequence flowchart

Charger		Vehicle
START		
Send start-of-charging signal (d1 ON)	→	Recognize start-of-charging (f ON)
Compatibility check	←	Transmit battery parameters: Max. voltage to stop charging, Target voltage, Total battery capacity, etc.
Transmit charger parameters: Max. output voltage, Max. output current, Error flag etc.	→	Compatibility check :Calculate Max. charging time
Recognize start permission signal (j ON)	←	Send start permission signal (k ON)
Connector lock and perform insulation test Send charging ready signal (d2 ON)	→	Recognize charging ready signal (g ON) EV contactor ON
Charging Current Control Output current Checking circuit condition, charging time etc.	←	Checking battery condition, temperature etc. Calculate optimal charging current Transmit charging current value in every 100ms Checking input current value and error signal
		Battery voltage becomes Max. value Terminate charging
Output zero current	←	Send zero current signal
Recognize charging stop (j OFF) Terminate charging process (d1 , d2 OFF) Connector unlock	←	Confirm zero input current EV contactor OFF Send charging stop signal (k OFF)

Figure 15: Flow diagram of the CHAdeMO chagrining protocol.

Once the user presses the ‘start charge’ button, the charger supplies 12V through ‘d1’ to the EV and excites the photocoupler at ‘f’. The EV detects this and transmits charging parameters (voltage and current limits, and battery capacity) via the CAN bus. The charger checks whether it is compatible and transmits its maximum voltage and current to the EV though the CAN bus. Once the EV is satisfied the charger is compatible, it conducts the transistor at ‘k’; this in turn tells the charger it has permission to enable charging. The charger then locks the connector and performs insulation and ground tests. This ensures the charger’s connector and cable are in working order, allowing charging to begin. The charger closes relay ‘d2’, which conducts the photocoupler at ‘g’ indicating to the EV the preparation procedures are complete and charging is ready to begin. Since both ‘d1’ and ‘d2’ are now closed, the EV can close its main battery contactor. This allows direct connection between the charger and EV battery pack for charging. The EV transmits the required current every 0.1 seconds through the CAN bus and charger supply this through constant current control. The EV constantly monitors the battery pack parameters (voltage, current, temperature etc.) and can stop the current four ways should a problem arise.

1) Request a zero current through the CAN bus.
2) Send an error message through the CAN bus.
3) Turn of the transistor at ‘k’, which removes the charging, enabled signal.
4) Opening of the EV battery contactor.

The charger is also monitoring its own voltage, current, and temperature for potential problems. Should a problem be detected, the charger sends the EV and error signal and stops the charging process. Stopping the charging process from the charger side and be done multiple ways depending on the charger topology. Examples include [15]:

1) Blocking of the gate drive signal on the switching converter.
2) Open the output contactor.
3) Open a circuit breaker on the input.

Once the charging has been completed the EV transmits a zero current request over the CAN bus and the charger stops outputting. Once the EV confirms zero current is flowing, the EV opens the battery contactor. The EV also sends the ‘disable charging’ signal by switching transistor ‘k’ off. Once the charger has detected zero output current it opens relays ‘d1’ and ‘d2’. The connector is unlocked and the charger procedure is complete.

Although the CAN bus could communicate all the data required for the charger, CHAdeMO prefers to use a combination of analogue and digital communication. The CHAdeMO association states this design improves the safety of the charger in three key ways [15]:

1) It prevents the erroneous start of charging due to malfunctions in the digital control system.
2) It can be confirmed that both control system in the vehicle and the charger are operating correctly at each step of the operation.

3) When the analogue signal is lost, the charging operation will be shut down immediately. As the result, shutdowns can be achieved faster than transmitting a digital signal. An important feature of this design is the fail-safe function.

Although the power for the EV battery contactor comes from the charger via ‘d1’ and ‘d2’, the EV still controls when the contactor is closed. This duel method improves safety by ensuring that without the connector in place, the EV battery contactor cannot close. This prevents the possibility of the EV battery bus voltage being present at the charge port terminals when no connector is present. Before the opening the contactor, the current must first have decreased significantly to reduce the possibility of the contactor welding shut.

8 References

[1] NZTA, "Monthly Light Vehicle Registrations March 2016," 2016.

[2] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *Power Electronics, IEEE Transactions on*, vol. 28, pp. 2151-2169, 2013.

[3] J. Dalidd. (2010, 30 April 2016). *What is EVSE? It's Electric Vehicle Supply Equipment, and here's what it's all about.*

[4] M. Brandl, H. Gall, M. Wenger, V. Lorentz, M. Giegerich, F. Baronti*, et al.*, "Batteries and battery management systems for electric vehicles," in *Proceedings of the Conference on Design, Automation and Test in Europe*, 2012, pp. 971-976.

[5] J. Cao, N. Schofield, and A. Emadi, "Battery balancing methods: A comprehensive review," in *Vehicle Power and Propulsion Conference, 2008. VPPC'08. IEEE*, 2008, pp. 1-6.

[6] (30 April 2016). *Battery Management Systems (BMS)*. Available: http://www.mpoweruk.com/bms.htm

[7] O. EVSE. (30 April 2016). *Electric Vehicle Charging. J1772 / OpenEVSE*. Available: https://open-evse.googlecode.com/files/J1772.pdf

[8] NEMA. (30 April 2016). *EVSE Powering the Electric Vehicle*. Available: https://www.nema.org/Products/Documents/nema+evse+presentation+for+communities.pdf

[9] T. Motors. (30 April 2016). *Supercharger*. Available: https://www.teslamotors.com/supercharger

[10] D. Herron. (2015, 30 April 2016). *EV DC Fast Charging standards – CHAdeMO, CCS, SAE Combo, Tesla Supercharger, etc*. Available: http://longtailpipe.com/ebooks/green-transportation-guide-buying-owning-charging-plug-in-vehicles-of-all-kinds/electric-car-charging-advice-systems/ev-dc-fast-charging-standards-chademo-ccs-sae-combo-tesla-supercharger-etc/

[11] H. Alliance. (30 April 2016). *HomePlug Green PHY™: perfect fit for Smart Energy / Internet of Things (IoT) applications Home Tech Resources HomePlug Gre*. Available: http://www.homeplug.org/tech-resources/green-phy-iot/

[12] CHAdeMO. (30 April 2016). Available: http://www.chademo.com/

[13] C. Association. (30 April 2016). *CHAdeMO Interface*. Available: http://chademo.com/pdf/interface.pdf

[14] T. Anegawa, "Safety Design of CHAdeMO Quick Charger and its impact on Power Grid," *Presentation. TEPCO,* 2010.

[15] T. Anegawa, "Safety Design of CHAdeMO Quick Charging System," *World Electric Vehicle Journal*, vol. 4, pp. 855-859, 2010.