Design and implementation of a CHAdeMO Interface on-board vehicle for vehicle-to-grid Applications

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Abstract—**In the last decade, the number of Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) have increased significantly. EVs and PHEVs will play an important role in the future of smart grid technology by storing the surplus energy in batteries and feeding it back into the distribution network when needed. Currently, only those EVs and PHEVs, which are equipped with the Japanese CHAdeMO standard (e.g. Nissan, Mitsubishi and Kia), are capable of feeding energy back into the electric grid. In order to enable Vehicle-to-Grid (V2G) functionality for already existing EVs and PHEVs, which cannot feed energy back into the distribution network, CTC cartech company designed and implemented the Vehicle CHAdeMO Interface (VCI) prototype, which fully implements the physical and protocol level of the CHAdeMO standard and manages the communication between the vehicle and the charger. The aim of this paper is to show the design, implementation and testing of the VCI. Some experimental test results are also displayed which validate the performance of this prototype. The significant advantage of VCI is that it can be installed in an EV or a PHEV without performing drastic changes in the already existing vehicle's Battery Management System (BMS) and it also allows bidirectional charging/discharging operation.**

Keywords—CHAdeMO interface, CHAdeMO protocol, Vehicle-to-Grid, V2G, Smart Grid, Electric Vehicles

I. Introduction– Concept

Car manufacturers are preparing to phase out vehicles powered solely by Internal Combustion Engines (ICEs) as the governments all over the world are planning to tackle fuel emissions. The growth in EVs and PHEVs is rising and by the year 2025, EVs and PHEVs will account for an estimated 30% of all vehicle sales [1]. Since the number of EVs and PHEVs is increasing significantly and in order to be able to use these vehicles sustainably and without emissions, a supply of electricity from renewable energy is indispensable. As these energy resources are decentralized and intermittent, the V2G concept will allow EVs and PHEVs to play an important role in the future of Smart Grid technology by storing the surplus energy in batteries and feeding it back into the distribution network when needed. In this scheme, EVs and PHEVs will act as flexible distributed stationary accumulators which are able to store and release electrical energy in order to compensate peak production and to support and stabilize the distribution nets, in case of huge absorption [2].

At the time of writing this paper, only those EVs and PHEVs which are equipped with the Japanese CHAdeMO standard (Nissan, Mitsubishi, and Kia) are capable of feeding energy back to the electric grid [3]. According to the preliminary figures of "The Electric Vehicle World Sales Database" (EV-Volumes.com), the number of EVs and PHEVs sold in the world in 2018 surpassed 2 million, which lead to the global cumulative plug-in number to be over 5 million (2008-2018). Of these 5 million plug-ins, two thirds are EVs and one third are PHEVs. Over 760,000 plug-ins are equipped with a CHAdeMO inlet and a total of almost 1.3 million plug-ins can use CHAdeMO [4].

Due to these figures and the forecast of the EVs in the future, the aim of this paper is to design, implement and test the VCI which can be installed in any EV that is currently only charged by Alternating Current (AC) Charging Stations, in order to enable the Direct Current (DC) fast charging and V2G functionality using an additional CHAdeMO vehicle inlet unit.

The structure of this paper is as follows: In section II, the CHAdeMO protocol is generally described along with the layout of the CHAdeMO vehicle inlet unit. The design concept and the components of the VCI are described in section III. The hardware and software implementation of the CHAdeMO protocol are explained in detail in section IV. In section V, the Hardware in the Loop (HiL) setup is shown. The results of testing are shown in section VI. Furthermore, the packaging design and the final prototype are revealed in section VII. A conclusion is stated in section VIII.

II. CHAdeMO Protocol Description

The CHAdeMO protocol is an EV/PHEV charging/discharging protocol developed by CHAdeMO Association. This protocol enables DC fast charging and delivers power in the range of 6kW to 200kW [5]. CHAdeMO is a contraction of the French term "charge de move", which means "let's charge and move". The name is derived from the Japanese phrase "let's have some tea", referring to the fact that the vehicle can be charged in a timespan which is equivalent to having a cup of tea. The CHAdeMO fast chargers generally aim to charge the EV/PHEV batteries up to 80% capacity within less than 30 minutes [6].

The CHAdeMO protocol describes all the necessary steps which must be followed before, during and after the charging/discharging operation. Once the charging connector belonging to the charger is mated with the EV/PHEV receptacle, the communication between the charger and the vehicle is initiated. Before the charging/discharging operation of the vehicle battery pack is initiated, the charger locks its connector, performs insulation and ground tests in order to ensure that the charger's connector and cable are in working order and without any fault [6].

In order to control the charging/discharging operation, the charger and the vehicle exchange Controller Area Network (CAN) messages containing the control and status information with each other. The vehicle provides battery characteristics information like maximum charge/discharge current allowed, maximum charge/discharge time etc. and the charger informs the vehicle about the charger characteristics like available output voltage/current, error thresholds etc. via CAN communication. The charging/discharging operation only begins after insulation test, ground tests and the initial exchange of control and status CAN messages between the charger and vehicle are performed as per the standards mentioned in the CHAdeMO protocol. After the charging/discharging operation is complete, the CAN communication between the charger and vehicle is stopped and the connector can be unplugged.

The CHAdeMO protocol uses a dedicated connector designed specifically for performing DC fast charging/discharging operation. Figure 1 depicts the pin layout of the CHAdeMO vehicle inlet unit. This connector has two DC power pins, one ground pin, five analog pins and two CAN pins [7]. Therefore, the connector has 10 pins in total. The two CAN pins are used to transfer data digitally between the charger and the vehicle. The analog pins are used to switch transistors and they establish analog communication between the charger and the vehicle [6].

III. Design Concept

In order to incorporate the CHAdeMO protocol in the vehicle, the DC power lines of the CHAdeMO connector at the vehicle must be interfaced with the vehicle battery pack and the digital and analog communication lines of the vehicle

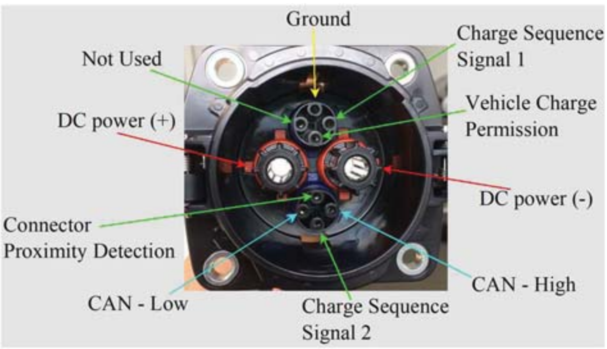

Figure 1: Pin layout of the CHAdeMO vehicle inlet unit [7]

connector must be interfaced with an intelligent electronic device like a microcontroller. This microcontroller must also communicate periodically with the vehicle BMS in order to obtain battery characteristic information like battery charging/discharging time, current etc. After receiving the battery characteristics from the BMS, the microcontroller must then forward this information to the charger using CAN communication. In order to fulfil the mentioned requirements, the VCI device is designed as depicted in Figure 2 and is installed inside the vehicle.

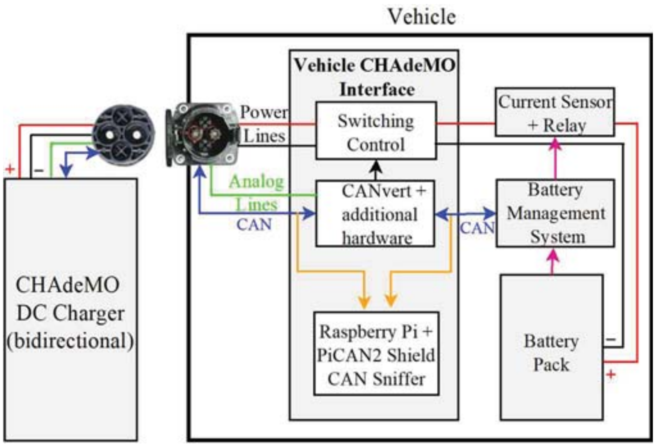

Figure 2: System Block Diagram of the Vehicle

The VCI consists of four components (three main and one optional):

1) *CHAdeMO connector:* The CHAdeMO connector (vehicle inlet) acts as an input to the VCI and is placed outside the VCI box. Figure 1 illustrates each pin of this connector.

2) *Switching Control:* This component consists of three relays. These relays are electrically operated switches. They are used to make or break electrical contact between two isolated devices. Out of the three relays, two are high-power relays and are placed in series with the DC power lines. These relays are used to make connection between the power lines from the charger and the vehicle during charging/discharging process and disconnect when this process ends. The low power relay is used to control the operation of the high-power relays.

3) *CANvert and additional hardware:* As depicted in Figure 3, CANvert is a product designed by CTC cartech company GmbH which is capable of flexible bidirectional transmission of CAN messages. This device consists of a microcontroller and has also several digital and analog inputs/outputs [8].

   CANvert is best suited to implement and execute the CHAdeMO protocol as it provides CAN communication interface and the analog inputs/outputs necessary for the execution of the CHAdeMO protocol.

Figure 3: CTC cartech company CANvert product [8]

As illustrated in Figure 2, the CAN interface pins of the CHAdeMO connector are directly connected to the CAN interface of the CANvert. Similarly, the analog pins of the CHAdeMO connector at the vehicle side are connected to the respective analog pins of the CANvert. The CANvert controls the low-power relay of the switching control module.

The additional hardware along with CANvert as depicted in Figure 2 consists of optocouplers. These optocouplers are used to transfer electrical signals between two circuits (charger and VCI) by using light signal while keeping the circuits electrically isolated from each other.

4) *CAN sniffer (optional):* CAN sniffer is a tool which records all the CAN messages transmitted over the CAN bus network. In VCI, Raspberry Pi along with CAN interface shield (PiCAN2 board) is used as CAN sniffer. CAN sniffing is useful to track down the errors caused during the operation of the VCI.

As a summary, VCI is an electronic device comprising of relays, optocouplers and a microcontroller circuit (CANvert) which is interfaced with the CHAdeMO connector (vehicle inlet) and which implements the CHAdeMO protocol for performing DC fast charging/discharging (V2G) operation of an EV or a PHEV.

IV. Hardware and Software Implementation

The implementation of the VCI comprises of two main tasks. The first task involves hardware assembly of VCI circuit as per the standards mentioned in the CHAdeMO protocol specification. The second task is the implementation of the CHAdeMO protocol sequence, indicating the steps to be followed before, after and during the process of charging/discharging. This sequence flowchart is implemented in the CANvert microcontroller device.

A. Vehicle CHAdeMO Interface Circuit

Figure 4 illustrates the VCI circuit diagram, showing the electrical connections between the charger and the VCI in detail. When the CHAdeMO connectors at the charger and the VCI are mated, the DC power lines of the charger are electrically connected with the EV/PHEV batteries via high-power relays "relay c1" and "relay c2" as depicted in Figure 4. These high-power relays are placed inside the VCI and are controlled by both the charger and the VCI. The charger provides 12 Volt (V) DC power to operate the relays while the VCI controls these relays via a low-power relay "relay e". Both the high-power relays can be only closed when the low power relay (relay e) is closed by the VCI.

The CHAdeMO connector outlet has five analog lines out of which one is unused. The four used analog lines are "charge sequence signal 1", "charge sequence signal 2", "connector proximity detection" and "vehicle charge permission". As seen in Figure 4, each of these analog lines is connected to one optocoupler, which provides electrical isolation between the VCI and the charger. The charger informs the VCI that the coupling is successful by closing "relay d1" and setting "charge sequence signal 1" line to 12V [9]. When the charger performs ground and insulation tests, it informs the VCI that it is ready to charge/discharge the vehicle battery by closing

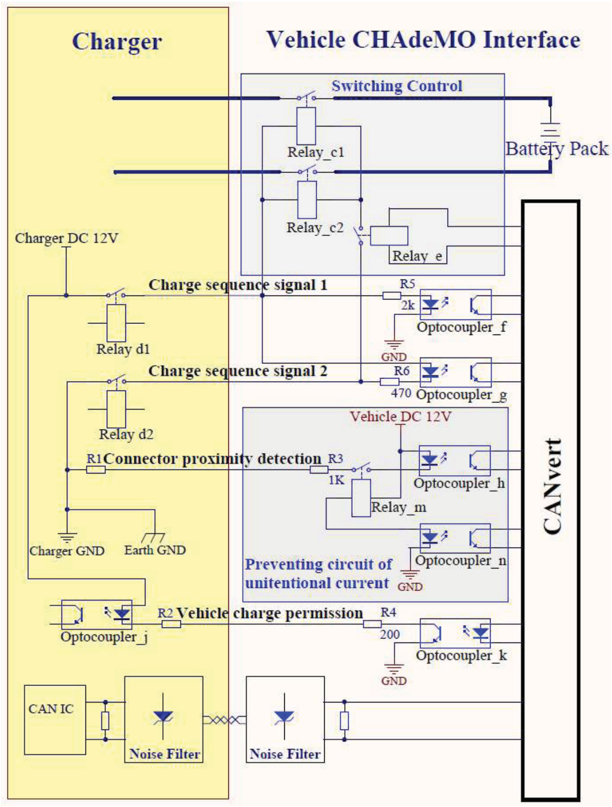

Figure 4:Vehicle CHAdeMO Interface Circuit Diagram [5]

"relay d2" and setting 0V on the "charge sequence signal 2" line.

The "connector proximity detection" line is used by the VCI to indicate the parking/ignition status of the vehicle. If the vehicle is not parked (ignition on), the CHAdeMO connector at the charger and the VCI side are assumed to be disconnected and the vehicle battery charging/discharging process must not be performed in such a scenario. If the vehicle is parked, the "connector proximity detection" line is set to 12V by the VCI.

The "vehicle charge permission" line is used by the VCI to indicate to the charger that the vehicle is ready for charging/discharging. This line is set to 12V when the VCI indicates the charger that the vehicle is ready for charging/discharging operation. The status of the "connector proximity detection" and the "vehicle charge permission" lines is also shared by the VCI to the charger via CAN status messages.

The combination of analog communication along with digital CAN transmission improves the safety level of the system. Due to analog and digital communication, it is confirmed that both VCI and the charger control systems are operating correctly at each step of the charging/discharging sequence. Moreover, when an analog signal is lost, the charging/discharging operation is shut down immediately by the VCI and the charger, ensuring a fail-safe system functionality [9].

B. CHAdeMO Protocol Sequence

In this section, the sequence of analog and digital communication steps taking place between the charger and the VCI during the charging/discharging process is explained in detail and is shown in Figure 5. The steps for charging and discharging operation are the same, except the direction of the current. During the charging process, the current enters the battery and during discharging, the current leaves the battery.

When an operator presses the start button of the DC fast charger, which is connected to Smart Grid, the charging/discharging process is initiated. The charger closes "relay d1". Then 12V control voltage is supplied from the charger to the VCI through "charge sequence signal 1" analog line which excites the "optocoupler f" [9]. At this point, the VCI recognizes that the charging/discharging operation has commenced and it wakes up the BMS and retrieves battery characteristic information (battery voltage etc.) from the BMS. The VCI then forwards this information to the charger via CAN messages.

After the charger receives CAN messages from the VCI and confirms that it can charge/discharge the vehicle, the charger transmits its characteristic information (available output current/voltage, error thresholds etc.) to the VCI via CAN messages. The VCI checks the vehicle's compatibility with the charger based on the transmitted data. If it does not find any compatibility problems, it sets the "vehicle charge permission" line to 12V [10].

When 12V are available on the "vehicle charge permission" line, the charger recognizes that the vehicle has given permission to begin charging/discharging operation. Then the charger locks the connector and performs ground and insulation tests. Conduction of insulation test confirms that there are no short circuit or ground fault abnormalities present, which can be caused due to aging or the abuse of connector cables. When the insulation test is completed, the charger closes "relay d2" and informs the VCI that the initial setup for charging/discharging is complete. The vehicle recognizes that the initial setup at the charger is complete via "optocoupler g" and finally EV/PHEV battery charging/discharging operation is performed [9]. During the charging/discharging operation, VCI periodically communicates important battery information e.g. State of Charge (SOC), required charging current, etc. with the charger.

When the SOC of the battery is 100% or when the user normally stops charging/discharging, the VCI informs the completion of charging/discharging operation to the charger via CAN control message. Then the charger terminates supplying current to the battery during charging or stops receiving the current from the battery during discharging. The VCI then terminates the charging/discharging session by setting 0V on the "vehicle charge permission" line. The charger receives the charge/discharge termination information via "optocoupler j". Afterwards, the VCI confirms that the current on the DC power lines is less than 5 Ampere (A) and then it opens the EV contactor relays by opening the low-power relay (relay e). Meanwhile, the charger terminates the charging/discharging session by setting optocouplers "d1" and "d2" off and it unlocks the connectors. In case of an error (e.g. system fault), the VCI informs the charger to terminate process by sending the required CAN messages and then the high-power relays are opened.

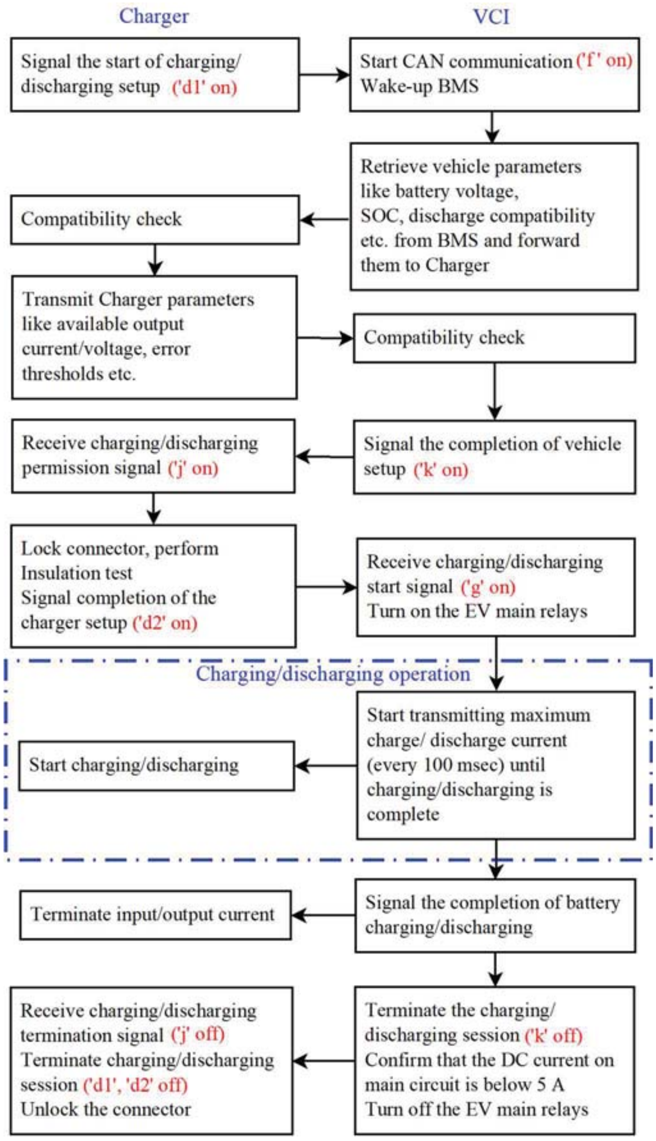

Figure 5: CHAdeMO Protocol Sequence [10]

V. HARDWARE IN THE LOOP LAB SETUP

Figure 6 depicts the Hardware in the Loop (HiL) setup where the charger and the BMS are simulated in order to test the analog and digital communication functionalities of the VCI as per the standards mentioned in the CHAdeMO protocol. In this lab setup, no power transfer is performed between the vehicle and charger and vice-versa.

The charger and the BMS functionalities are simulated using the Vector CANalyzer [11]. Vector CANalyzer is a universal analysis and simulation tool for vehicle networks and distributed systems developed by Vector Informatik GmbH. The VN1630A CANalyzer PRO is used in this project and it has four CAN channels. Out of the four CAN channels, one channel is used for transmitting the charger CAN messages and the other CAN channel of the CANalyzer is used to transmit BMS messages.

In this setup, two power supplies are used. One to power the microcontroller of the VCI while the other is used to represent the charger side. Multimeters are used to make continuity check (i.e. check relays are on or off) and to measure voltages on various analog and digital lines. Raspberry Pi along with the PiCAN2 shield is used to log the

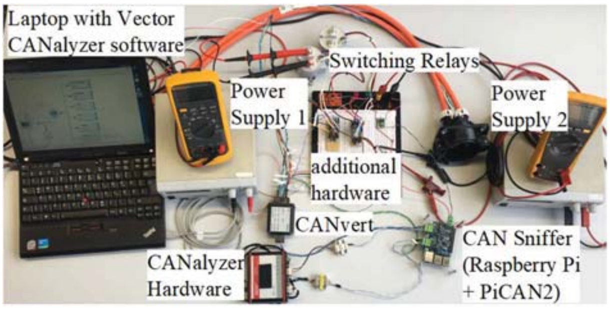

Figure 6: Vehicle CHAdeMO Interface Hardware in the Loop Lab Setup

CAN messages exchanged between the charger, VCI and the BMS. The additional hardware in Figure 6 depict the VCI optocouplers and low power relay (relay e). The high-power relays were disconnected from the load and a multimeter was used to perform continuity tests during operation. This setup is called as HiL setup because only the hardware components of the VCI are present and all the other devices are software simulated. Using the HiL lab setup as illustrated in Figure 6, the VCI device functionalities were tested.

VI. Experimental Results

This section describes the results when the VCI is operated in the HiL setup, consisting of the simulated charger and vehicle's BMS. Figure 7 shows the results when charging operation is performed.

In Figure 7, the charging operation is triggered after four seconds from the recording of results. After one second, the charger sets 12V on the "charge sequence signal 1" line by closing "relay d1". When the VCI receives the charging request from the charger, it starts sending the required CAN messages to the charger, it checks if it is compatible with the charger and sets the "vehicle charge permission" line to 12V (by turning on switch "k") indicating that it is ready to be charged. Meanwhile, the charger also checks its compatibility with the vehicle and when the vehicle is ready to be charged, it locks the connectors, performs the ground and insulation tests and then sets the "charge sequence signal 2" to 0V (by closing "relay d2") indicating that the vehicle and the charger are both ready to start the charging process.

Afterwards, the VCI closes the low-power relay (relay e), which leads the EV contactors to be closed and the charging process to be started. As per Figure 7, the EV contactors are closed 13.5 seconds after "relay d1" is closed. This time is affected by the CHAdeMO protocol and the time sequence set in the CANalyzer. Thus, the initial activities performed by the charger and the VCI after the connectors are plugged and before initiating the charging process take only few seconds and this time is unnoticeable by the operator.

In this HiL simulation test setup, the charging operation is performed approximately for 17 seconds and then the normal stop operation from the vehicle is triggered and the "vehicle charge permission" line is set to 0V. In response, the charger terminates the charging current flow. The VCI then opens the high-power relays via "relay e". Afterwards, the charger opens the relays "d1" and "d2" and then unlocks the connectors.

VII. Final Prototype

After the testing phase was completed, a case for placing the VCI components was designed. Figure 8 shows the packaging design of the VCI case. All the components are fitted inside a 250 x 255 x 97.5 mm (L x W x H) case. In order to prevent electromagnetic interference from the high voltage to the low voltage side, the case is divided into two

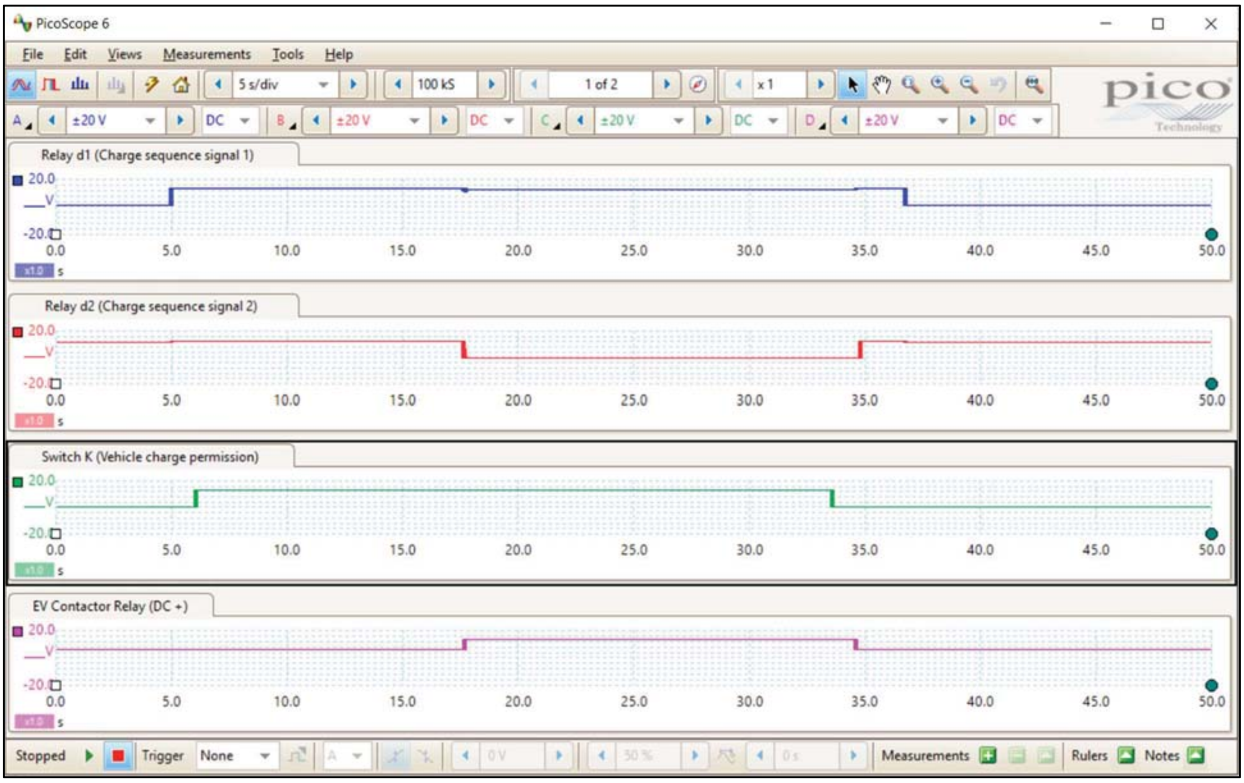

Figure 7: Vehicle CHAdeMO Interface Operation Results

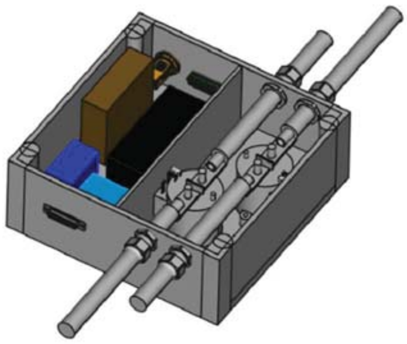

Figure 8: Packaging design of the Vehicle CHAdeMO Interface case

compartments using an isolation material. The high-voltage side consists of the two high-power relays.

Figure 9 depicts the top and side views of the VCI case. Figure 9 (a) shows the top view of the VCI case. The three Light-Emitting Diodes (LEDs) are used for indicating the status of the VCI operation. The charge, discharge and error statuses are identified by the LEDs. Figure 9 (b) depicts one side of the VCI box. This side provides the interfaces to the vehicle BMS. Two DC High Voltage (HV) cables, one D-Sub 15 connector and one Universal Serial Bus (USB) connection are present at this side of the VCI. The D-Sub provides interface to the CAN and digital/analog lines of the vehicle BMS and also the power to operate the VCI box. The USB port is needed (temporarily) for data logging.

Figure 9 (c) depicts the other side of the VCI box. This side provides the interfaces to the CHAdeMO connector (vehicle inlet). Two DC HV cables and one D-Sub 15 connector are present at this side of the VCI. The D-Sub connector at this side provides interface to the CAN and analog lines from the CHAdeMO connector.

VIII. CONCLUSION

In this paper, the design, implementation and testing phases of the Vehicle CHAdeMO Interface (VCI) device are described. The hardware and software implementations are based on the CHAdeMO protocol and specifications. A Hardware in the Loop (HiL) lab setup is established for testing and the performance of this device is validated by the experimental results. Finally, the packaging design and the top/side views of VCI are revealed.

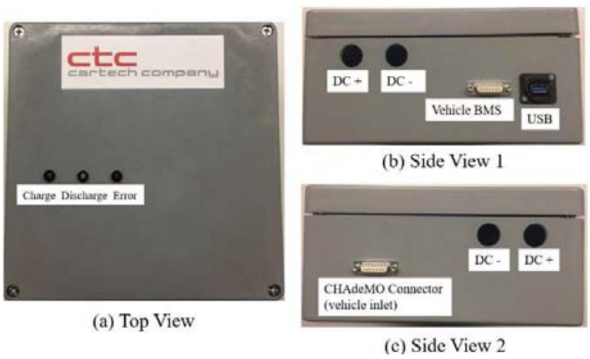

Figure 9: Vehicle CHAdeMO Interface Case Top and Side Views

The VCI is a prototype developed by CTC cartech company. This device can be installed in a vehicle which normally has no V2G functionality, in order to enable and control DC fast charging/discharging (V2G) without performing multiple changes in the vehicle's BMS. As the number of EVs/PHEVs increases, this device can play an important role in the future by allowing the vehicles to store and release electrical energy in order to support and stabilize the smart grid.

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