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Chandra Mouli, Gautham Ram; Kaptein, Johan; Bauer, Pavol; Zeman, Miro

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Implementation of Dynamic Charging and V2G using Chademo and CCS/Combo DC charging standard

Gautham Ram Chandra Mouli[1], Johan Kaptein[2], Pavol Bauer[1], Miro Zeman[1]
[1]Dept. of Electrical Sustainable Energy, Delft University of Technology, Netherlands
[2] ABB B.V. EV Charging Infrastructure, Netherlands
G.R.ChandraMouli@tudelt.nl, Johan.Kaptein@nl.abb.com, P.Bauer@tudelft.nl, M.Zeman@tudelft.nl

Abstract- **Dynamic charging of electric vehicles (EV) refers to charging the EV using variable charging power. This is important for applications where the EV is charged from intermittent renewable energy sources like wind or solar. Dynamic charging can be implemented using three standards - AC charging, DC charging via Chademo and CCS/COMBO. This paper compares the charging standards in their implementation of dynamic charging and vehicle to grid (V2X) and brings out its influence on the charging system design, response time, flexibility in charging from renewable sources and buffer capacity that is required. Experimental results of dynamic charging using Chademo and CCS/COMBO are presented for different compatible EV that shows the fundamental difference between the two standards.**

I. Introduction

Charging of electric vehicles (EV) can be done today with AC or DC charging[1][2]. AC charging is done using the on-board AC/DC power converter of the EV using a single phase or three phase AC connection. Currently, there exits three types of AC charging systems used globally [3]–[7] as shown in Fig. 1 and Table I:

1. Type1 SAE J1772-2009, single phase charger used in US
2. Type 2 Mennekes VDE-AR-E 2623-2-2, single and three phase charger used in Europe
3. Tesla dual charger for single phase AC and DC

Due to space and weight restrictions on the EV, AC charging is limited to Level 2 charging power levels of up to 22kW (Three-phase 400V, 32A). In the US, the Type 1 plug provides for single phase charging using three power pins – namely phase (L1), neutral (N) and earth pin (E). The Type 2 plugs used widely in Europe supports three-phase charging using five power pins - three phase pins (L1,L2,L3) and neutral (N) and earth pin (E). The IEC61851-1 standard defines charging mode for AC charging namely Mode 1, Mode 2 and Mode 3. In case of Mode 1 and mode 2, the charging power is derived from a standard non-dedicated power socket and mode 2 has an additional in-cable protection device built into it. Mode 3 makes use of a dedicated electric vehicle supply equipment (EVSE) where the EVSE has both control and protection functionality built into it. This is the preferred charging mode for public charging stations and for residential charging at high powers.

For high power charging of EV beyond 50kW, DC charging is used. DC charging comes under Mode 4 charging as defined in IEC61851-1, where a dedicated off-board AC/DC converter supplies DC power directly to the EV's battery. Since off-board chargers are unrestricted by space and weight constraints of on-board chargers, they can go up to Level 3 charging power levels of 240kW, as shown in Table I. Currently, there exist three types of DC charging systems used globally [5]–[8] as shown in Fig. 2 and Table I:

1. Type 4 CCS/COMBO (Combined Charging System)
2. Type 4 Chademo
3. Tesla dual charger for single phase AC and DC

The three systems use three power pins for transferring the power namely - two DC power pins DC+, DC- and one earth pin (E). They differ however in the communication and control protocol used. For example, Chademo uses CAN bus communication and uses a total of 7 pins for control and communication while CCS uses Power Line Carrier communication (PLC) and 2 communication pins. It is important to note that both Type 1 and 2 AC charging and type 4 DC charging via CCS uses the same physical pin for communication and control. The charging system of Tesla is unique in the respect that it uses the same two power pins for both single phase AC and DC and two communication pins. The Tesla coupler and interface are designed in such a way that the EV can be charged using a Tesla charger (either AC or Supercharger) or using an adapter from a Type 1 SAE J1772 charger or a CHAdeMO charger.

II. Dynamic Charging Vs Static Charging

Dynamic charging as used here refers to charging an EV with variable power. This is in contrast to static charging where the EV is charged with a constant power. The term dynamic charging must not be confused with dynamic 'on-road' charging which refers to charging a car while driving [9]. The benefits of dynamic charging are:

1. To match EV charging with uncontrollable renewable generation like solar or wind [10]–[13]
2. To match EV charging with variable grid prices so as to optimize the cost of charging [14], [15]

Dynamic charging is hence a method of demand side management by which the mismatch between renewable generation and load can be minimized without the use of additional storage systems. This gives benefits of reduced cost of charging, lower reserve generation capacity in the grid, lesser grid violations due to EV charging and reverse flow of renewable generation. The key to implementing

TABLE I

AC AND DC CHARGING PLUGS, POWER LEVELS IN EUROPE AND THE US BASED ON [5], [6], [3], [4]

	Plug	Number of pins Communication	Charging level	Voltage & current	Maximum power
US	Type1 SAE J1772	3 power pins – L1,N,E 2 control pins – CP, PP (PWM over CP)	AC Level 1	1Φ 120V, upto 16A	1.9 kW
			AC Level 2	1Φ 240V, upto 80A	19.2 kW
Europe	Type 2 Mennekes	4 power pins – L1,L2,L3,N,E 2 control pins – CP, PP (PWM over CP)	AC Level 1	1Φ 230V, upto 32A	7.4 kW
			AC Level 2	3Φ 400V, upto 32A	22 kW
SAE	Type 4 SAE J1772 CCS	3 power pins – DC+,DC-,E 2 control pins – CP, PP (PLC over CP, PE)	*DC Level 1*	200-450V DC, upto 80A	36kW
			DC Level 2	200-450V DC, upto 200A	90kW
			DC Level 3	200-600V DC, upto 400A	240kW
Chademo	Type 4 Chademo	3 power – DC+,DC-,E 7 control pins (CAN communication)	DC Level 3	200-500V, upto 125A	62.5kW
	Tesla US	3 power pins – DC+,DC-,E 3 power pins (reused) – L1,N,E 2 control pins – CP, PP	DC Level 3	For Model S, 400V, upto 300A	120kW

Fig. 1. Plug for AC charging- US Type 1 SAE (left), European Type 2 Mennekes (middle) and Tesla plug (right)[1]

Fig. 2. Plug for DC charging – CCS/Combo charger for US (left), European (middle) and Chademo plug (right) [1]

[1] Images were taken from [5], [6], [3], [8] or used under CC license

dynamic charging is the communication and control protocols in different charging systems. This shall be investigated in detail in this paper.

A. Dynamic charging via AC charging

Communication between EV and the charger for AC charging is done using a control pilot (CP) and proximity pilot (PP). The proximity pilot keeps track of the physical connection between the charger and EV and communicates the maximum ampacity of the charger cable. To implement dynamic charging:

- The control pilot has a PWM signal that can be adjusted to modify the maximum charging current that is available from the charger, as shown in Fig. 4 as the ‘variable set point’.
- Based on the PWM signal on CP, the EV decides the charging current based on the status of the battery such as the state of charge (SoC) and temperature. The charging current request is hence set by the EV, which is the MASTER and the current requested by the EV can be less than or equal to the maximum charger current.
- The charger is the SLAVE and supplies the current requested by the EV. If the EV battery SoC or temperature is too high, the battery management system of the EV will draw a current lower than the set point. For example in Fig. 4, the EV SoC is too high in the ‘CV’ region and the battery goes into constant voltage charging and draws a current that is lower than the set point. Thus by controlling the PWM on the CP, dynamic charging can be implemented.

The Smart Charging Controller developed by Cohere in collaboration with the authors [16] used this technique to dynamically charge the EV based on the local PV generation and local residential consumption.

B. V2X via AC charging

V2X is the general terminology that corresponds to discharging the EV to supply power to a home (V2H), building (V2B), load (V2L) or to a grid (V2G). Since EV owners may not be willing to make a separate investment for a DC charger at home, V2X via on-board AC chargers has a

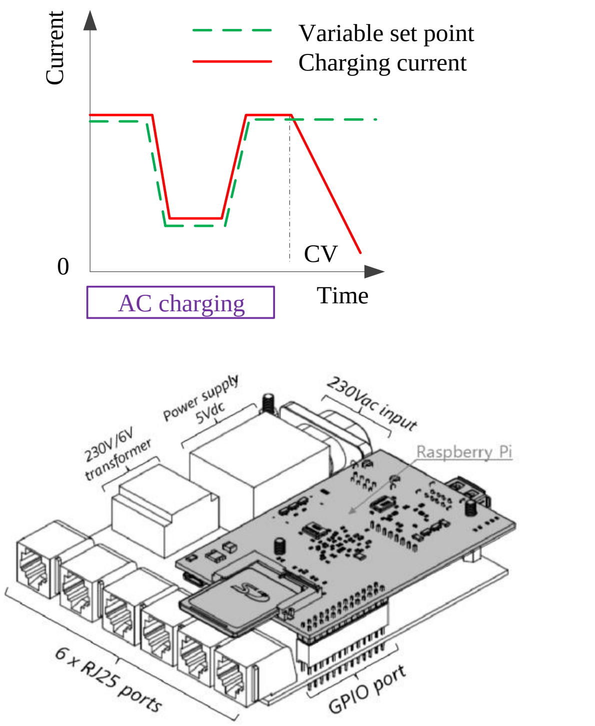

Fig. 3. Dynamic charging using AC charging via Type 1 or Type 2 plug (top). 3D rendering of the SCC hardware (bottom) [16]. The device collects measurements from current transformers and controls the charging power

huge potential for the future. Secondly, the V2X power levels of 10kW [8] are of the same order of the power levels of on-board chargers. However, implementation of V2X using AC chargers is currently not possible due to two reasons:

1. EVs currently in the market are not equipped with bidirectional on-board chargers that support EV discharging.
2. Communication protocol for AC charging via CP, PP has no provision for initiating V2X. In V2X mode, the charger acts like the MASTER and requests the EV for discharging a required amount of current. However in current AC charging protocol, the EV is the MASTER and such a V2X request cannot be enabled.

To overcome the two barriers, EV manufacturers should look into the possibility of installing bidirectional chargers on-board EV. If communication on the CP, PP for AC charging can be integrated to include PLC as with CCS (will be discussed later in the paper), the opportunity for V2X via AC chargers can be realized.

III. Dynamic Charging via Chademo

Chademo v1.0 charging control mechanism is similar to the AC charging for type 1 and type 2. The car is the MASTER and decides the required charger current and sends a current request command every 200ms. The charger is the SLAVE and supplies the required currents. The charging protocol is as follows:

- The EV and charger make a handshake to:
  - Share information on the EV like model, battery voltage and SoC
  - Set the upper charging current limit based on the maximum charging power of the EV and the charger.
- EV continuously makes a current set point every 200ms based on the battery like SoC, temperature, etc.
- Charger has to supply the request current, with a current resolution of 2.5A. So the charging current supplied by the charger can vary from the set point of the EV by up to 2.5A
- The maximum current set point of charger and EV set at handshake remains constant throughout for Chademo v1.0. There is no mechanism for the charger to request a change of maximum limit. So essentially dynamic charging is not possible. This is unlike AC charging where the upper set point of the charger current can be set continuously with PWM on the CP. Secondly, Chademo v1.0 does not have the facility for V2X. This is due to two reasons. Firstly, the v1.0 necessitates the presence of a diode at the charger output which will only allow charging and V2X.

Secondly, the communication protocol does not have a facility to make the charger the MASTER, to set the charging current and direction. This is implemented in Chademo v2.0 V2X where the output diode is not required:

- The EV and charger make a handshake to share information on the EV battery. The maximum charging and discharging current are set based on the power ratings of the EV and the charger.
- Once charging begins, EV continuously sets the maximum current for charging and discharging every 200ms as shown in Fig. 4 based on the battery characteristics like SoC, temperature, etc. When the maximum discharge current is zero, it means that V2X is not possible.
- The charger can provide any charging current between the upper and lower bounds with a resolution of 2.5A as seen in Fig. *4*. This essentially means that a varying PV power can be translated into a varying EV charging current as long as it is within the upper and lower bounds. In Fig. *4*, it can be seen that at the start of the graph, the SoC is low and the maximum discharge current (negative limit) is small. The discharge current limit increases as SoC increases with charging. At the left of the graph, the battery is nearly full and the maximum charging current limit is slowly reduced by the EV to prevent overcharging the EV batteries.

Hence, Chademo v2.0 facilitates dynamic charging with high flexibility. A smart energy management system can decide on the optimal charging profile of the EV based on user preferences, energy prices or renewable generation and it can be implemented via dynamic charging.

CCS/COMBO facilitates dynamic charging and V2X by using PLC communication over the CP, PP. This allows high-level communication overcoming the limitations of only using PWM for communication in AC charging. The implementation of V2X and dynamic charging for CCS varies from Chademo and is explained in the next section.

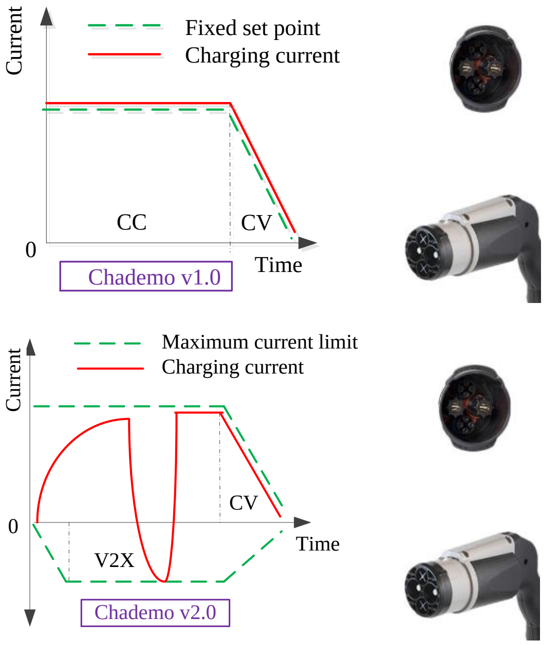

Fig. 4. Static charging using Chademo v1.0 (top) and dynamic charging using Chademo v2.0 (bottom)

IV. DYNAMIC CHARGING VIA CCS/COMBO

- The EV and charger make a handshake to share information EV and set the maximum charging current limit based on the power rating of the EV and the charger.
- Once charging begins, EV and charger continuously negotiate and set a charging/discharging current set point based on the battery characteristics like SoC, temperature, etc. For V2X or dynamic charging, the charger can make a request for change of current and EV has to accept this request. The communication is based on ISO 15118.
- If the request is accepted, EV changes the current set point and the charger has to charge/discharge the EV based on the negotiated set point as shown in Fig. 5. The current resolution is 2.5A.

Dynamic charging with CCS is hence not as flexible as in Chademo. If the EV charging current has to change from I_1 to I_2 due to a sudden change of renewable generation or energy prices, the EV charger will need to send a request for a new set point as shown in Fig. 5. It takes time t_1 for the car to respond to the new request and it changes the set point from I_1 to I_2 over the time t_2. For the period $(t_1+ t_2)$, a buffer capacity E_{buff} is required to store the energy from the renewable source or the grid. This buffer capacity is not necessary with Chademo.

$$E_{buff} = V_{batt}(I_1 - I_2)\left(t_1 + \frac{t_2}{2}\right) \tag{1}$$

t_1 and t_2 are mainly dependent on the manufacturer of the EV, SoC of the battery and the current set points I_1, I_2. As per the CCS standard, the EV can take up t_1=60s to respond to the request for a new current setpoint from the charger. This is very long time considering the fact that many V2X or dynamic charging applications like providing ancillary services or changing the charging power in correspondence to renewable generation would require the EV to respond within few seconds (<=2s or less). Secondly, the CCS standard is silent on the time limit t_2 that can be taken by the EV to change the current setpoint from I_1 to I_2. t_2 can be as high as 10s or more, as shown in the next section. Both of these are serious drawbacks from the point of view of dynamic charging as it makes the EV susceptible to be slow in response. While manufacturers can design their EV to respond much quicker, the fact that a 60s response time for t_1 and no upper limit for t_2 makes the COMBO implementation slow in theory and requiring a large buffer capacity E_{buff}.

V. EXPERIMENTAL VERIFICATION

A. Dynamic charging and V2X using Chademo

An experimental setup was built to implement the dynamic charging of EV and V2X. The schematic of the setup is shown in Fig. 6 where a bidirectional charger is used with a Chademo compatible EV. CAN bus communication is used between the EV and charge protocol interface that implement the Chademo v2.0 protocol. A standard ABB EV charger was used for charging the EV and a commercially available solar inverter was used for discharging EV for V2X. In the experiment, the charge protocol for Chademo v2.0 was implemented for dynamic charging and V2X by changing the EV from charging mode to discharging mode and back, as seen in the waveforms in Fig. 6. Using the AC/DC rectifier module, the EV is first charged at -4A current (sign convention: negative current denotes charging and a positive

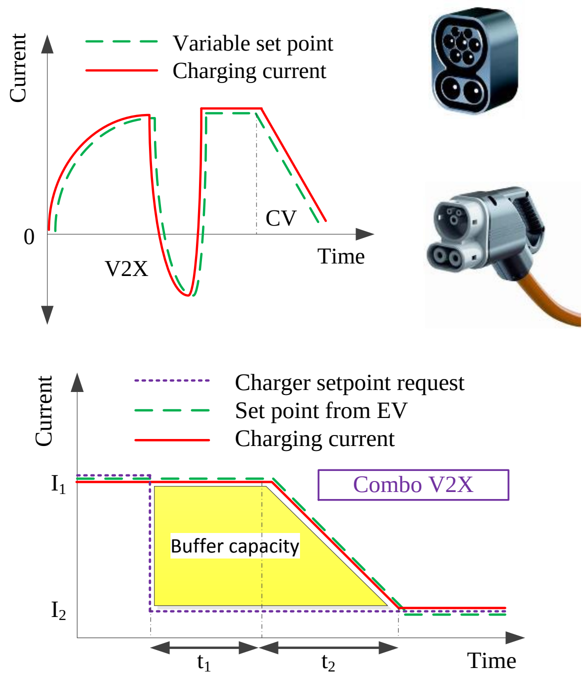

Fig. 5. Dynamic charging and V2X using CCS/COMBO (top) and the required buffer capacity (bottom)

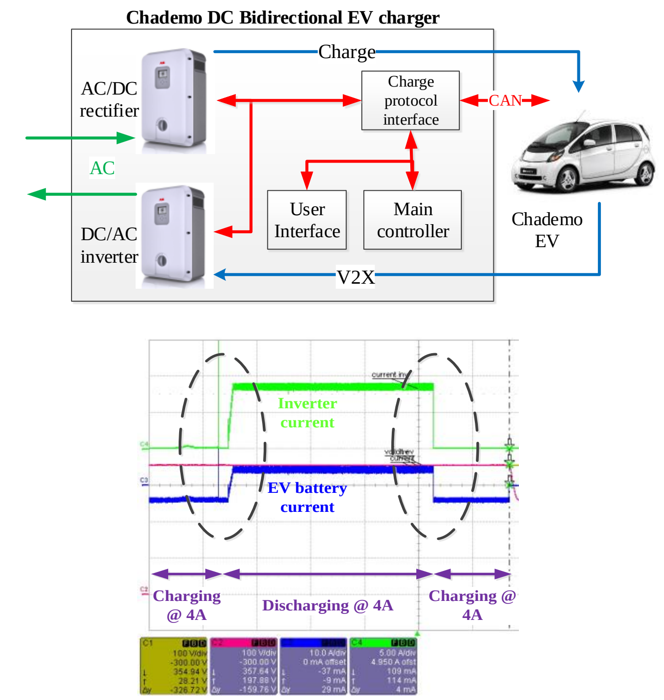

Fig. 6. Experimental setup for dynamic charging and V2X using Chademo v2.0 (top) and experimental waveforms (bottom). Chademo uses CAN bus communication between charger and EV.

current is discharging). Using the main controller, the current is then varied by the charger at 20A/s slope to +4A current for V2X operation. The solar inverter module draws DC current from the EV and supplies it back to the grid as seen by the green waveform. Due to lack of CAN bus communication with inverter module, the AC/DC rectifier module continue to supply 4A, so inverter draws 4A each from the EV and from the charger module, totaling 8A. Such a mechanism can hence be used in relation to a smart charging system that varies the charging to match the renewable generation or grid energy prices.

B. *Dynamic charging and V2X using CCS/Combo*

An experimental setup using an ABB 50kW Terra 53C CCS charger as shown in Fig. 7 was used to test dynamic charging on two CCS compatible EV. The charge protocol interface in the EV charger is used to send PLC signals to the EV to control the charging current. The main controller was used to send charging current commands *Iref* every 100ms to the EV as shown in Fig. 8. The EV continuously sends a current request command *Iset* every 100ms and the EV charger then supplies the requested current *Iset* via the CCS charger plug. When there is a change in the charger current command *Iref*, EV has to respond within $(t_1 + t_2)$ as discussed in the previous section.

Dynamic charging was implemented on two different CCS compatible EV and tested for comparing their performance. Fig. 8 shows the dynamic charging of both the EVs with varying EV charging current indicated by *Iset*. Fig. 8 (top) shows the measurement of charger current reference *Iref* requested by the charger every 100ms over PLC and the

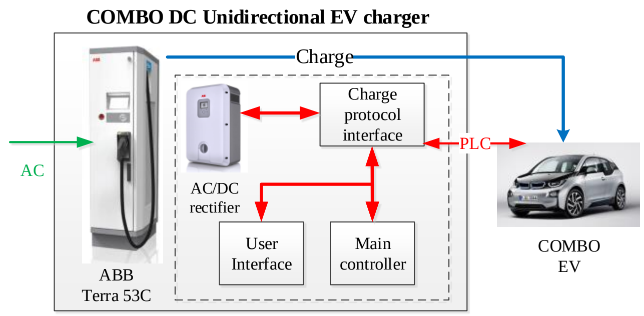

Fig. 7. Experimental setup for dynamic charging using CCS using a 50kW ABB Terra 53C charger. CCS uses PLC communication on CP between charger and EV.

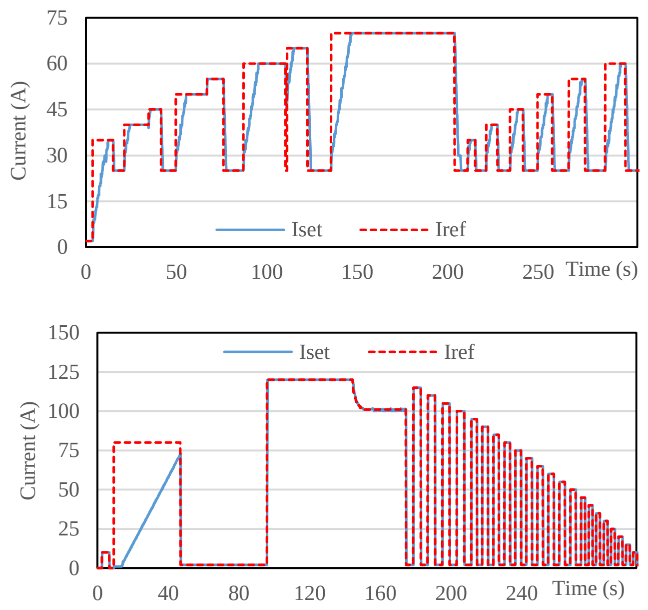

Fig. 8. Measurement of charger current reference *Iref* sent every 100ms over PLC and corresponding EV current request *Iset* for CCS compatible EV of manufacturer 1 (top) and manufacturer 2 (bottom).

corresponding EV current request *Iset* as a function of time for EV 1. It can be seen that the EV responds immediately by changing the setpoint *Iset* with t_1 =100ms. However to change the setpoint *Iset* from I_1 to I_2, the EV takes a long time t_2 depending on how big is the difference between I_1 and I_2. For example, when the setpoint *Iref* is increased from 25A to 70A at t=135.6s, the EV responded by changing the setpoint *Iset* in approximately t_2=10s. On the other hand, when the setpoint *Iref* is decreased, the EV response is relatively faster and t_2 is in the order of 0-2s depending on I_1, I_2. Thus, the EV responds quickly when the setpoint is reduced while the response is much slower when the setpoint is increased. While the response times of 100ms is within the stipulated 60s limit as per CCS, the total time $(t_1 + t_2)$ is very long when a fast response to the order of <2ms is required for dynamic charging and V2X applications.

On the other hand, the behavior of EV 2 was found to be quite in contrast. In Fig. 8, it can be seen that when the charging session is to begin, a current setpoint of 10A is used to test the EV-charger connection and protection mechanism before initiating the charging. Then a charger current reference of *Iref*=80A is sent. The EV responds over a time of $(t_1+ t_2)$=38s when *Iset* increases from 0A to 70A.

Interestingly, this relatively slow response occurs only during startup. After that, when the current setpoint from charger *Iref* was changed, the EV responded within $t_2=100ms$ as shown in Fig. 8. The time taken was irrespective of the difference between I_1, I_2 and whether the charger setpoint *Iref* was increasing or decreasing. Rapid dynamic charging with fast change of current reference from the charger could hence be tested and implemented as shown in Fig. 8 for t=180s to 280s. The current reference *Iref* was changed every 5s and the EV responded within 100ms. This was much lower than the response time of first CCS EV that was tested. Such an EV with fast response time of the order of 100ms would hence be excellent for use in dynamic charging and V2X applications. The experimental tests go to show the dynamic charging can be implemented using a CCS/COMBO electric car and how the performance of the charging varies from EV to EV.

VI. CONCLUSIONS

Dynamic charging and V2X correspond to the method of charging EV with variable charging power and supplying energy back to the grid respectively. The two technologies have huge potential for the future to match the EV charging with local renewable energy production, providing grid support and ancillary services and optimizing the cost of charging EV. In this paper, the implementation of dynamic charging and V2X using AC charging (SAE J1772, Mennekes) and DC charging via CCS/COMBO and Chademo is analyzed in detail. It has been shown that AC charging can offer dynamic charging via PWM on control pilot while V2X is not currently possible due to the absence of on-board bidirectional EV chargers.

Chademo, CCS/COMBO and Tesla supercharger are the three main DC charging standards currently in use which uses an off-board EV charger. Chademo v2.0 offers maximum flexibility for dynamic charging and V2X. The EV only sets the maximum currents for charging and discharging and the charger has maximum control to vary the charging current and direction within these limits. On the other hand, CCS provides for negotiated dynamic charging where the EV charger sends current commands every 100ms and EV is required to respond within a time frame of $(t_1+ t_2)$ seconds. The CCS standard currently allows the EV to take up to t_1=60s to respond to the charger current request. The standard is silent on the upper limit for the response time t_2. The $(t_1+ t_2)$ response time as stipulated by the standard slow considering that any real-world dynamic charging and V2X application would require the EV to respond fast within milliseconds or few seconds. Hence, it would be advisable if CCS sets an upper limit for t_2 would reduce the response time to the order of $(t_1+ t_2)$ =1-2s in the future.

Experimental results of dynamic charging have been presented that prove the fundamental differences between using Chademo and COMBO for different compatible EV. A Chademo compatible EV was moved from charging to V2X state using the Chademo v2.0 protocol. Dynamic charging was implemented on two different CCS compatible EV and the two EV exhibited very different response time.

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