Direct Current Fast Charger System Characterization: Standards, Penetration Potential, Testing, and Performance Evaluation

1021743

Direct Current Fast Charger System Characterization: Standards, Penetration Potential, Testing, and Performance Evaluation

1021743

Technical Update, December 2011

EPRI Project Managers

J. Halliwell
A. Maitra

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION PREPARED THIS REPORT:

Electic Power Research Institute (EPRI)

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The following organization prepared this report:

Electric Power Research Institute (EPRI)
942 Corridor Park Boulevard
Knoxville, TN 37932

Principal Investigators
S. Rajagopalan
A. Maitra
J. Halliwell
M. Davis
J. Harding

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Direct Current Fast Charging System Characterization: Standards, Penetration Potential, Testing, and Performance Evaluation. EPRI, Palo Alto, CA: 2011. 1021743.

ABSTRACT

The importance of direct current (dc) fast charging of plug-in electric vehicles (PEVs) is expected to grow in the near future. This report presents a brief overview of the various standards and protocols in use and in development along with a market assessment of various dc fast chargers and compatible vehicles planned. Modeling and analysis were performed to evaluate the penetration of dc fast chargers based on vehicle driving patterns, region, and charger power. A 200-V, three-phase fast charger was installed at the Electric Power Research Institute (EPRI) laboratory in Knoxville, Tennessee. The charger was instrumented and data captured and analyzed to investigate various aspects of the charger, that is, charge profiles, efficiency, power factor, and power quality. This report details all aspects of this study.

Keywords

dc fast charger
CAN
CHAdeMO
Combo connector
EV
J1772
PEV
PHEV

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
AN OVERVIEW OF DC FAST CHARGER STANDARDS

Plug-in Electric Vehicles (PEVs) are now available in many North American markets, with more models expected to become available to consumers over the next 12 months. These vehicles will present utilities with opportunities as well as challenges as their numbers potentially grow to hundreds of thousands of vehicles connected to the electric grid for charging. The vehicles have the potential to represent hundreds of megawatts of new demand which will require appropriate support infrastructure. These vehicles represent a prime opportunity to support energy independence and environmental initiatives but will require a sensible planned approach to build out of infrastructure.

In order to support PEVs adoption in the market place, it is expected that consumers will demand faster charge rates especially for the all electric vehicles. Faster charge rates require higher power electrical charging systems. Because of the physical and electrical limits of the onboard charging systems, fast charging systems move the charger electronics, which convert alternating current (AC) from the grid to direct current (DC), off the vehicle and to the Electric Vehicle Supply Equipment (EVSE).

This chapter provides an update on the market status as well as an update on the status of various standards and connectors for DC fast charging.

Charging Levels and Standards Overview

While the recommended practice for AC charging of PEVs was completed within the Society of Automotive Engineers (SAE) in 2010, a recommended practice for DC charging of PEVs in the US has yet to be finalized. As with AC charging, the primary lead in establishing these standards for the US is SAE, which has four documents in various stages of completion that relate to DC charging of PEVs:

- SAE J2836/2 - Use Cases for Communication between Plug-in Vehicles and Off-Board DC Charger
- SAE J2847/2 - Communication between Plug-in Vehicles and off-board DC Chargers
- SAE J2931 – Power Line Carrier Communications for Plug-in Electric Vehicles
- SAE J1772 – SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler

SAE has defined AC charge levels by the AC input voltage to the vehicle. For DC charging, the voltage at which charging occurs is dependent on the vehicle battery and that battery's control system. As such, DC charge levels are not defined on voltage level, but instead, are defined by the power level of charging delivered. SAE has proposed three levels of DC charging to be considered in the recommended practice:

- **DC Level 1 –** 200-450V

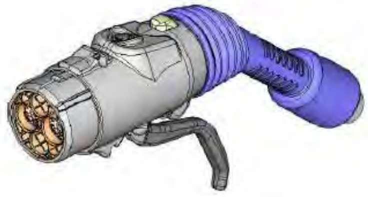
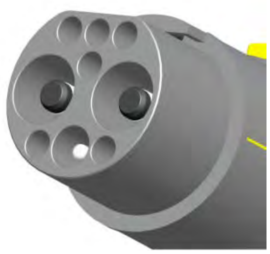
  - Rated Current <=80A
  - Rated Power <= 36kW
  - DC transfer using the existing J1772 AC connector
- **DC Level 2 –** 200-450V
  - Rated Current <=200A
  - Rated Power <= 90kW
  - DC transfer using either the combo connector or CHAdeMO connector
- **DC Level 3 –** 200-600V
  - Rated Current <=400A
  - Rated Power <= 240kW
  - Proposed connector is TBD

Connector Status

Currently, all electric vehicles with DC charging capability employ the CHAdeMO standard. This standard was developed in Japan by the Tokyo Electric Power Company (TEPCO) and the Japan Automotive Research Institute (JARI). The CHAdeMO charger is classified as a DC Level 2 charger by SAE. A number of companies have licensed the technology and are producing or planning to produce the chargers in the US.

For the US market, within the SAE J1772 Hybrid Task Force there has been proposed what is termed a “combo connector” (shown in Table 1-1). This connector combines the footprint of the J1772 AC coupler with a set of high current pins, allowing the connector to potentially be used for AC Level 1, AC Level 2, DC Level 1 and DC Level 2 charging with a single vehicle inlet. Prototype combo coupler vehicle receptacles and plugs are currently being tooled by 2 manufacturers (REMA and KET). The SAE J1772 committee has not finalized a connector decision as of this writing, but it is expected that a US DC connector standard will be completed in the first or second quarter of 2012. As noted in Table 1-1, at the international level there are several connectors being proposed as a solution for DC fast charging.

Table 1-1
Different DC Couplers Proposed in US, Europe, and Asia

 **CHAdeMO**	 **Type 2 Combo**
 **China**	 **J1772 Combo** **Type 1 Combo**

TEPCO/JARI CHAdeMO Connector

The CHAdeMO plug is shown in Figure 1-1 with the connector pinout shown in Figure 1-2. The CHAdeMO interface has been chosen as the national standard for DC fast charging in Japan and all electric vehicles available today with DC fast charging capability use this connector. Key aspects of the CHAdeMO connector are:

- Widely deployed in Japan. Being used in EV Project pilot demonstration in the US in the 2011 and 2012 timeframe.
- Standard includes 2 pins for direct CAN bus communication and defines full communication protocol and messaging.
- Based on floated output ("reference" ground) with ground monitor. UL has recently indicated that they would accept the reference ground concept if properly implemented.
- Requires 2 connectors on vehicle if AC charging capability is desired.

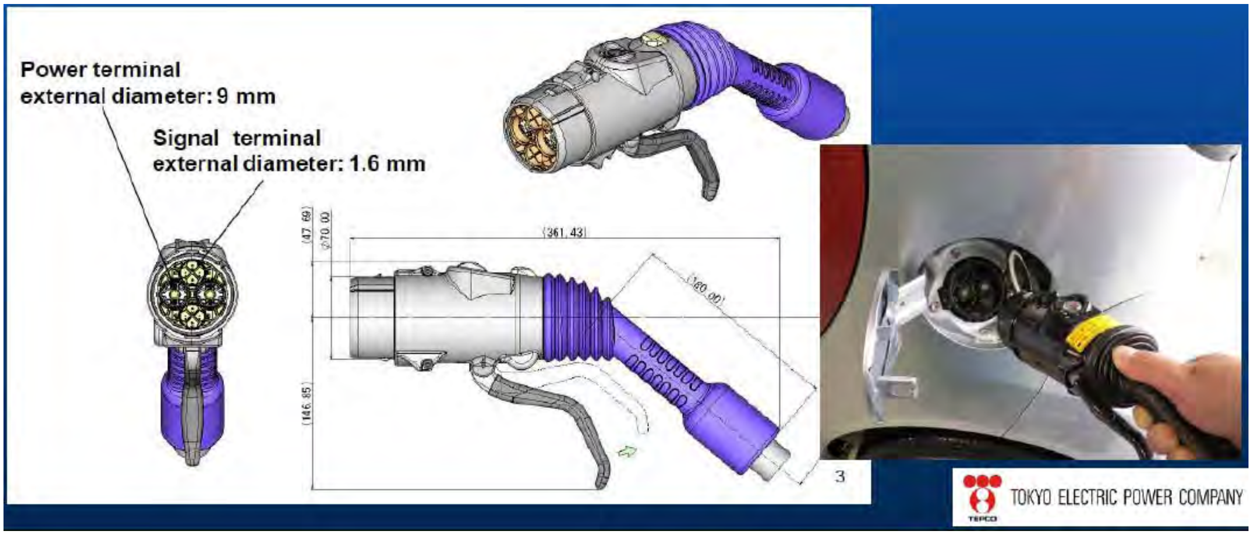
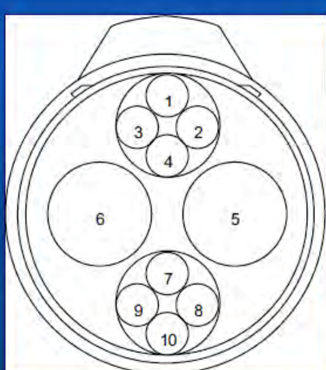


Figure 1-1
CHAdeMO Connector Plug and Receptacle



Pin No.	function / assignment	Pin diameter (mm)	Wire size (mm²)
1	Reference GND for insulation monitor	1.6	0.75
2	Control EV relay (1 of 2)	1.6	0.75
3	(not assigned)	1.6	—
4	Ready to charge control	1.6	0.75
5	Power (supply) line-negative	9.0	150A：42.4 200A：53.5
6	Power (supply) line-positive	9.0	150A：42.4 200A：53.5
7	Proximity detection	1.6	0.75
8	Communication +	1.6	0.75
9	Communication -	1.6	0.75
10	Control EV relay (2 of 2)	1.6	0.75

TOKYO ELECTRIC POWER COMPANY

Figure 1-2
CHAdeMO Connector Pinout

J1772™ Connector for DC Level 1 Charging

It has been proposed that the J1772™ AC connector could also be used for off-board DC charging. This has been termed DC Level 1 charging. As the J1772 AC connector does not have dedicated pins for communications, an alternate means of communication would be required to provide the control communications interface to an off-board DC charger.

It has been proposed within the SAE committee that is working on communications for PEVs (SAE J2836/J2847/J2953 Hybrid Committee) that power line carrier (PLC) communication over the Control Pilot wire be used as the primary interface for all vehicle communications. Testing is underway within the SAE effort related to selection of an appropriate PLC technology. The use of PLC over the Control Pilot wire is also being considered in Europe.

J1772™ Combo Connector Proposal

The SAE J1772 committee has been working to define the DC charging connector for DC Level 2 charging in the US (Figure 1-3). One of the proposals being considered by SAE is referred to as the combo connector as it combines the existing AC connector footprint with added high current DC charge pins. The combo allows for AC Level 1, AC Level 2, DC Level 1 and DC Level 2 charging with a single vehicle inlet.

Conceptual design of the combo connector has been completed. The initial design's mechanical assist feature was deemed too complicated and the overall coupler size too large. This resulted in a design requirements survey to rank key requirements in an attempt to reduce mechanical complexity and physical size. As a result, several design changes were made including:

- 8mm pins (200 amp); no communications pins; no mechanical assist.
    - o These options provide the highest current capability with the greatest incremental reduction in coupler width.
- Removal of communication pins reduced the coupler size and lowered the insertion force sufficiently to eliminate the need for mechanical assist.
    - – Requires Power Line Carrier (PLC) for DC charge control
    - – Current PLC direction is Green Phy on the Control Pilot circuit but other configurations are being tested

Other size reduction enablers:

- Revised DC sealing strategy
- Integrated AC keyway into DC terminal outer ring

Seven industry partners, including vehicle OEMs are tooling the combo coupler with 2 suppliers. Parts will be available beginning in late November, 2011. The combo connector supports hard earth ground. Communication specifications are being developed under J2847/2 and J2931 Task Force.

Debate continues within the SAE J1772 committee related to the status of the combo connector in relation to the CHAdeMO connector. A decision related to the ultimate connector solution is likely to occur in early 2012.

The subsequent revision to J1772 will include requirements for DC Level 1 and DC Level 2 charging. When J1772, J2847, J2931 and J2953 are published/re-published early next year, these documents will support a complete DC charging system.

Figure 1-3
Proposed SAE Combo Connector

Market Status

Several DC Fast Chargers have been released by manufacturers or are slated for release in the near future. Table 1-2 provides an overview of the various DC Fast Charger systems on the market today. Table 1-3 lists the vehicles available today with DC fast charging capability.

Table 1-2
DC Fast Charger Market Status

Manufacturer	DC Fast Charging Level/Standard	Input/Output voltage (V)	Power (kW)	Status
Nissan	Level 2/CHAdeMO	Unavailable	Unavailable	2013 estimate
Eaton	Level 2/CHAdeMO			On market
Aker Wade	Level 2/CHAdeMO	380/400/415/480/600 VAC/0-400 VDC	50	On market
AeroVironment	Level 2-3/CHAdeMO	480VAC to 600VAC/50-600 VDC	50	On market; Listed to UL standards
Coulomb Chargepoint	Level 2/SAE J1772™, CHAdeMO	480VAC to 600VAC/240-500 VDC	50	On market
Blink ECOtality	Level 2/CHAdeMO	208/380/400/480/575/200VAC/450 VDC	60	On market; Listed to UL standards
Epyon	Level 2/CHAdeMO		50	On market
Evtronic	Level 2/CHAdeMO			
Schneider Electric	Level 2/CHAdeMO			
SGTE Power	Level 2/CHAdeMO			
CIRCONTROL	Level 2/CHAdeMO			

Table 1-3
Vehicles with DC Fast Charging Capability

Manufacturer	Vehicle	Country
Nissan	Leaf	US
Mitsubishi	i-MiEV	US
Citreon	C-ZERO	France

2
DC FAST CHARGER MARKET PENETRATION – MODELING AND ANALYSIS

Market Penetration Introduction

DC Fast Charging is a topic of much debate- whether to install or not, where to install, how many to install and what power level to install are all questions that need to be answered. Infrastructure can be expensive to install - too much of it will result in overspending and wasted resources, while too little may result in stranded drivers. These problems will need to be addressed on a case-by-case basis, as there are limited policies and guidelines for installations. However, analysis of current driving patterns can provide some insight as to the amount of DC fast charging infrastructure needed.

Understanding the way vehicles drive is important to assess the amount of infrastructure required for both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). However, data resources on driving patterns are limited. The generally accepted standard for vehicle data analysis is the 2009 National Household Travel Survey (NHTS)[i]. The NHTS is a periodic, federally-funded survey of the U.S. households whose purpose is to provide information on daily and long distance travel patterns. For the 2009 NHTS, 150,147 households completed the survey. Surveyed respondents provided data on household makeup, personal demographics, vehicle characteristics and travel during a specified travel day. This in effect provides a snapshot of total driving characteristics that may not be representative on an aggregate basis. This dataset is used in the analysis.

The NHTS can be used to both model charging behaviors as well as understand everyday driving behaviors. First, it is important to realize the amount of driving that actually takes place in the US, on average, any given day. Figure 2-1 shows the distribution of driving behaviors for weekdays, weekends and all days. The y-axis on the left corresponds to the individual bin breakdowns and the y-axis on the left corresponds to the cumulative distribution. Total daily driving distances are binned in ten-mile increments with one added bin for vehicle that were not driven.

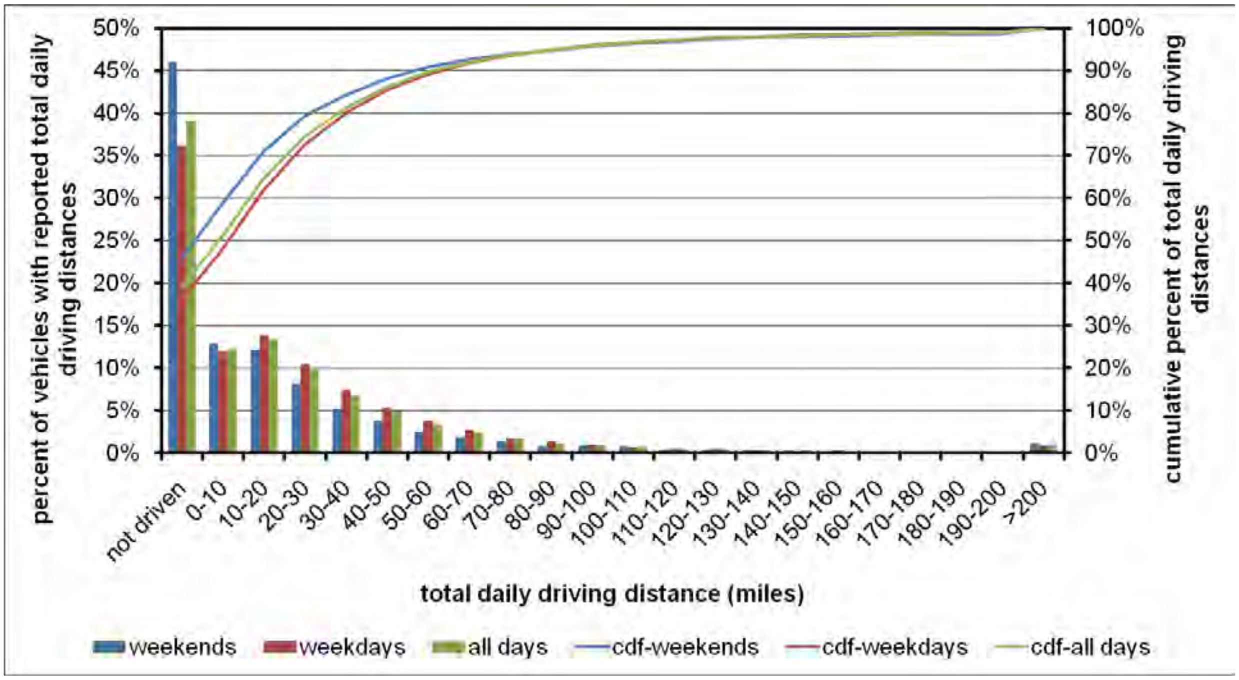


Figure 2-1
Distribution of day type driving behavior (Source: 2009 NHTS)

The distribution of driving behavior for both weekdays and weekends shows the relatively short distances most individuals drive – when the vehicles are even driven. For 96% of the vehicle days sampled in the 2009 NHTS the vehicles are driven **less than** 100 miles on the sample day, implying the need for DC fast charging to be small. Real world driving patterns will likely not allow for current BEVs to go the full 100 miles, but this still is a small portion of the vehicle population. The need for DC fast charging, based on aggregate daily driving distance, is assumed to be low.

The analysis performed to understand the actual need for DC fast charging is limited in nature as it does not include geographic information and gives only a one-day sample. Three cases are analyzed to understand the amount of DC fast charging that would actually be put into use:

- Case 1, assumes that a vehicle will drive until 20% SOC is reached, and fast charge as many times as needed to get through the day.
- Case 2, assumes that a vehicle is limited to one fast charge per day, and past that must use a different vehicle.
- Case 3, assumes that if a vehicle is going to drive more than 80 miles in one day and is in a multi-car household, another household vehicle is used for the days driving. If only one vehicle is in the household, the driver is allowed to fast charge as many times as necessary.

The analysis assumes that every individual will be ‘forced’ into a BEV100; in reality this is not true. Individuals will likely purchase vehicles that meet their particular needs. The analysis models all trips up to infinite length – many of these trips may not use a BEV100. The minimum value for fast charging is actually zero; DC fast charging is meant to be an enabler to encourage longer driving distances in BEVs and increase comfort levels of new drivers, but it is not meant to be the end-all. In the future, vehicle swapping will occur or alternate modes of transportation may be used in order to enable extremely long trips. This analysis provides an order-of-magnitude result as to the actual need of DC fast charging based on average daily driving behaviors.

Methods & Results

Data inspection of driving patterns is useful; however, in order to better answer the problem, a modeling approach is used. The model incorporates the 2009 NHTS driving patterns as an input to assess the overall need for fast charging based on varying the availability of level 2 charging (6.6 kW) and varying the rated charge power at the DC fast charger (50 kW vs. 100 kW). Two scenarios are used for the level 2 inputs, first, where vehicles charge while parked at home, and second freely charging, or charging wherever the vehicle is parked. Freely charging locations could be restaurants, workplace, shopping malls, church, etc. These models are need based and do not include geographic information, as a result there is a considerable amount of uncertainty associated as to how the vehicles and DC fast chargers would actually be used. Given these inputs, three models are used to determine the need for DC fast charging, based on aggregate level results and driving patterns.

Case 1: Unlimited DC Fast Charging

First, the vehicle drives and charges either at home only or freely charging (charging whenever the vehicle is parked), if the vehicle reaches 20% SOC, it fast charges. In this scenario, there is no limit to the number of DC fast charges in the day. The vehicle continues to drive and fast charge, as needed, until the trips for the day are concluded. Since all trips are included and driving patterns are not allowed to change, this is a relatively high estimate of charger demand. Figure 2-2 shows an overview of how the model processes the first case, unlimited DC fast charging.

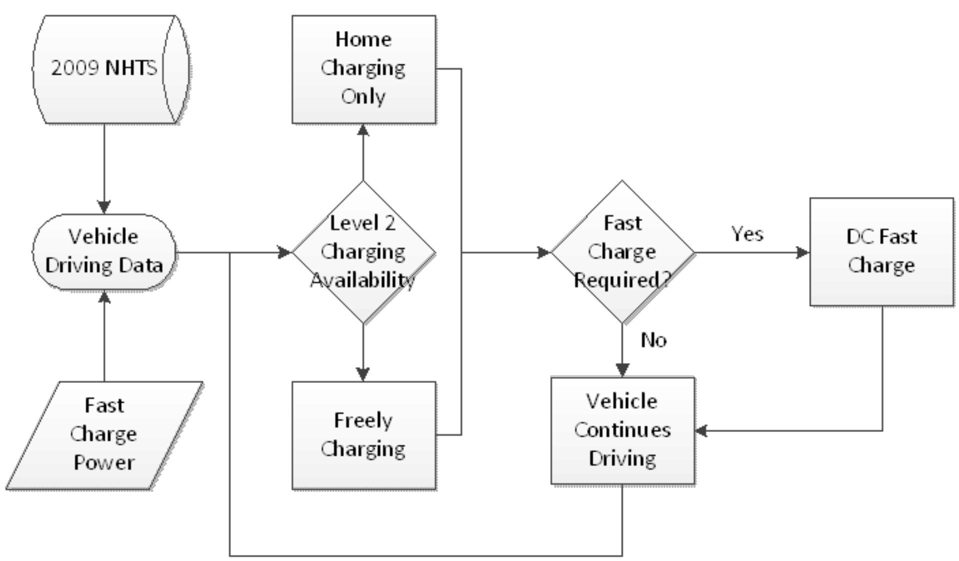


Figure 2-2
Case 1 model flow: unlimited fast charging availability

The results of the Case 1 show when 50kW chargers are in use based on charging availability and weekday type. The vertical axis of Figure 2-3 represents the numbers of chargers in use per

1,000 BEV100s and the horizontal axis represents the time of day the 50 kW chargers are in use. Figure 2-4 shows the same plot but for 100 kW chargers.

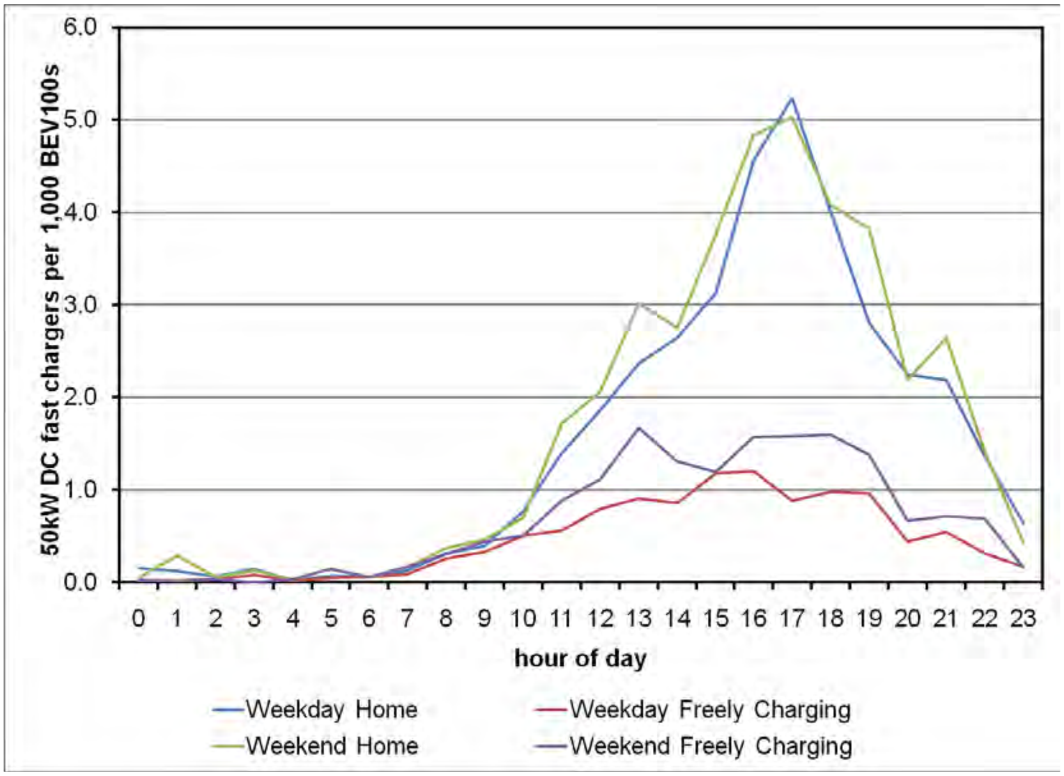


Figure 2-3
Case 1: 50kW DC Fast Charger use per 1,000 BEV100s

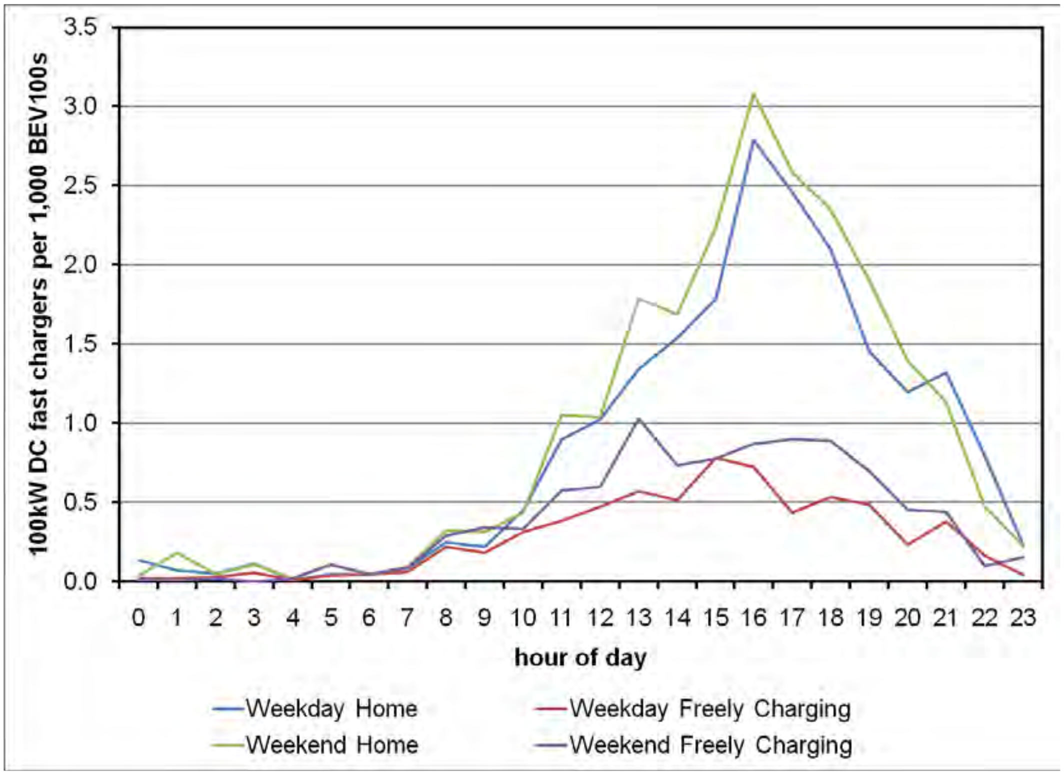


Figure 2-4
Case 1: 100kW DC Fast Charger use per 1,000 BEV100s

Figure 2-5 shows the maximum (between weekdays and weekends) for both charge powers and location scenarios for Case 1.

Table 2-1
Summary of Case 1 results – maximum number of DC fast chargers in use for both weekdays and weekends

	50 kW	100 kW
Home Charging Only	5.2	3.1
Freely Charging	1.7	1.0

DC fast charger use is relatively small (on the order of 5 per 1,000 BEV100s), but has a peak in the early evenings for both weekdays and weekends for both scenarios. The maximum value with freely charging decreases to less than 2 per 1,000 BEV100s for the 50kW scenario, and 1 per 1,000 BEV100s for the 100kW scenario. The higher charging power results in shorter charger dwell times – thus decreasing the maximum number in use at any given time. The behavior may be associated with longer commutes or may be related to longer-than-average driving behaviors on the sample day. DC fast charging is also impacted by the availability of level 2 charging – reducing the maximum use from 5 to 2 chargers in use. While it is unlikely that vehicles will be able to charge at every parking location, the results of the analysis show that increased charging availability can have on a greater impact on DC fast charging use than weekday behavior.

Allowing vehicles to DC fast charge an unlimited amount is not representative of what many vehicle drivers will likely do in real world applications. Drivers are unlikely to take a BEV100 on a several-hundred mile trip. As a result, this model represents a high estimate to the amount of DC fast chargers for the vehicle population.

Case 2: Limit One Fast Charge per Day

In the near term, BEV100s are unlikely to cover all trips. Trips of greater than one fast charge can be done using a different vehicle. For this case, it is assumed that a vehicle is only allowed to fast charge once in the day. And, past one charge the BEV is replaced with another vehicle. It is unimportant what type of vehicle that might be (PHEV, ICE, HEV, etc). Figure 2-6 shows the model flow for Case 2, the differences from Case 1 are highlighted in red.

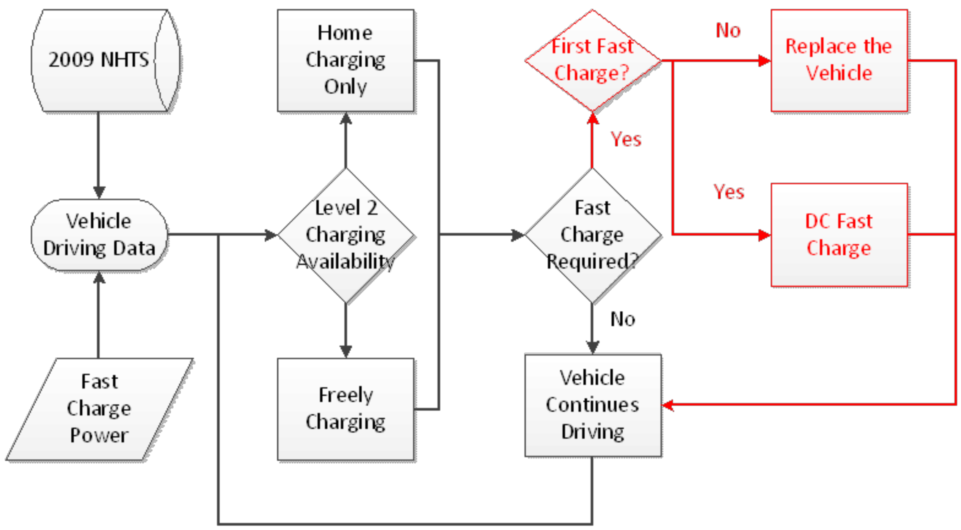


Figure 2-5
Case 2 model flow: limit one fast charge per day

The model follows the same processes as Case 1; the only difference is limiting the vehicle to one fast charge throughout the day. The results for the 50 kW case are shown in Figure 2-6. And the results for the 100 kW case are shown in Figure 2-7.

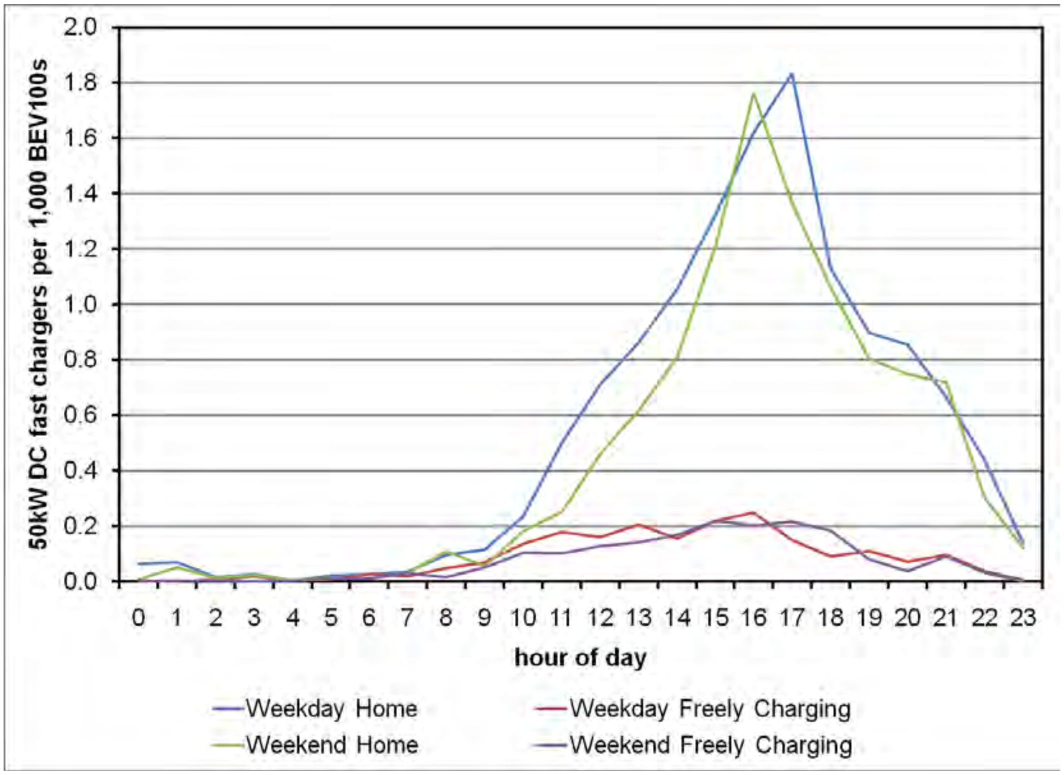


Figure 2-6
Case 2: 50kW DC Fast Charger use per 1,000 BEV100s

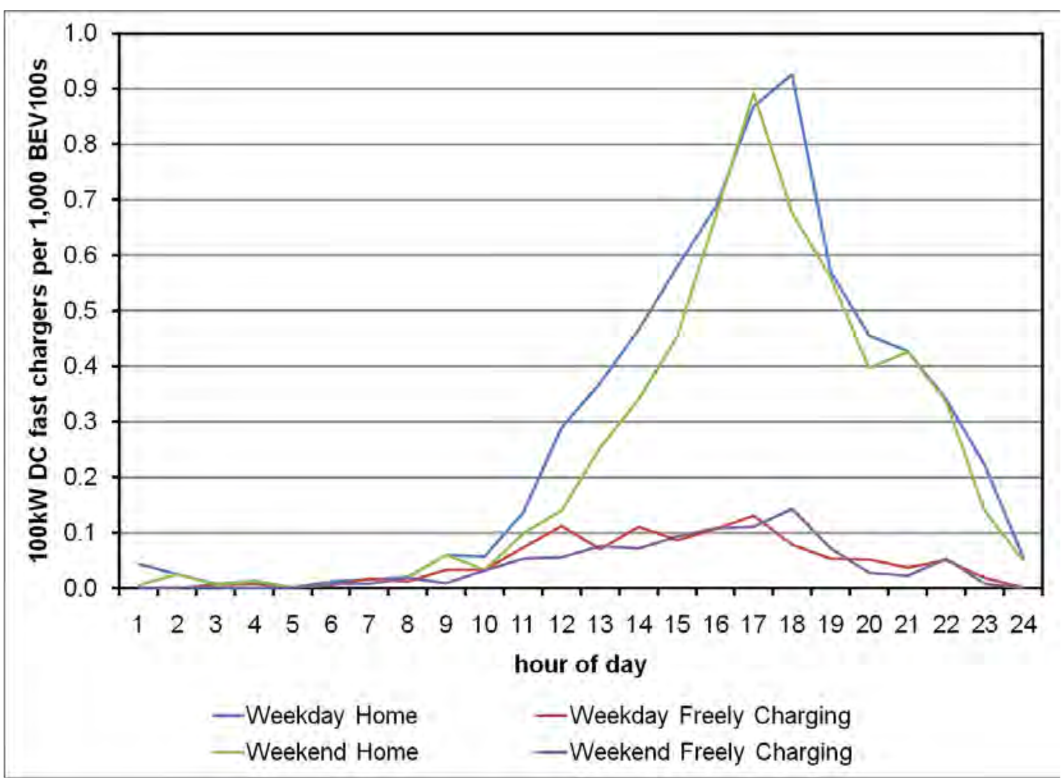


Figure 2-7
Case 2: 100kW DC Fast Charger use per 1,000 BEV100s

Table 2-2 summarizes the maximum charger use for Case 2.

Table 2-2
Summary of Case 2 results - maximum number of DC fast chargers in use for both weekdays and weekends

	50 kW	100 kW
Home Charging Only	2.6	1.4
Freely Charging	0.6	0.4

The number of DC fast chargers in use decreases by roughly half if fast charger use is limited.

Case 3: Household Vehicle Replacement

The last scenario analyzed is likely more representative of near-term, and current, BEV driving patterns. The NHTS provides data information on other household vehicles and demographics. For Case 3, the model assumes that if the vehicle drives more than 80 miles in one sample day (and may reach 20% SOC, needing a fast charge), and there is more than one vehicle in the household, the non-BEV would be used for that days driving. If there is no other vehicle in the household, the BEV is allowed to charge as many times as needed, similar to Case 1. The model flow is shown in Figure 2-8.

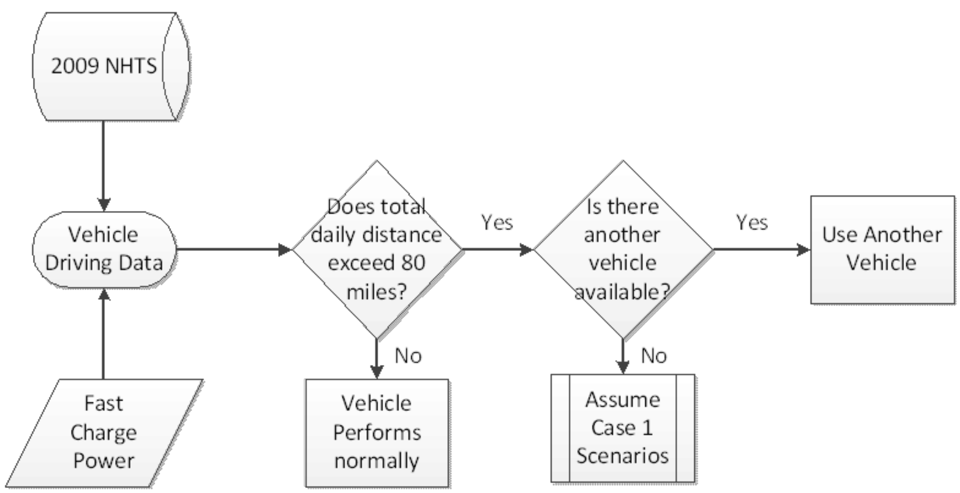


Figure 2-8
Case 3, household vehicle replacement

The results of the model are shown in Figure 2-9 and Figure 2-10.

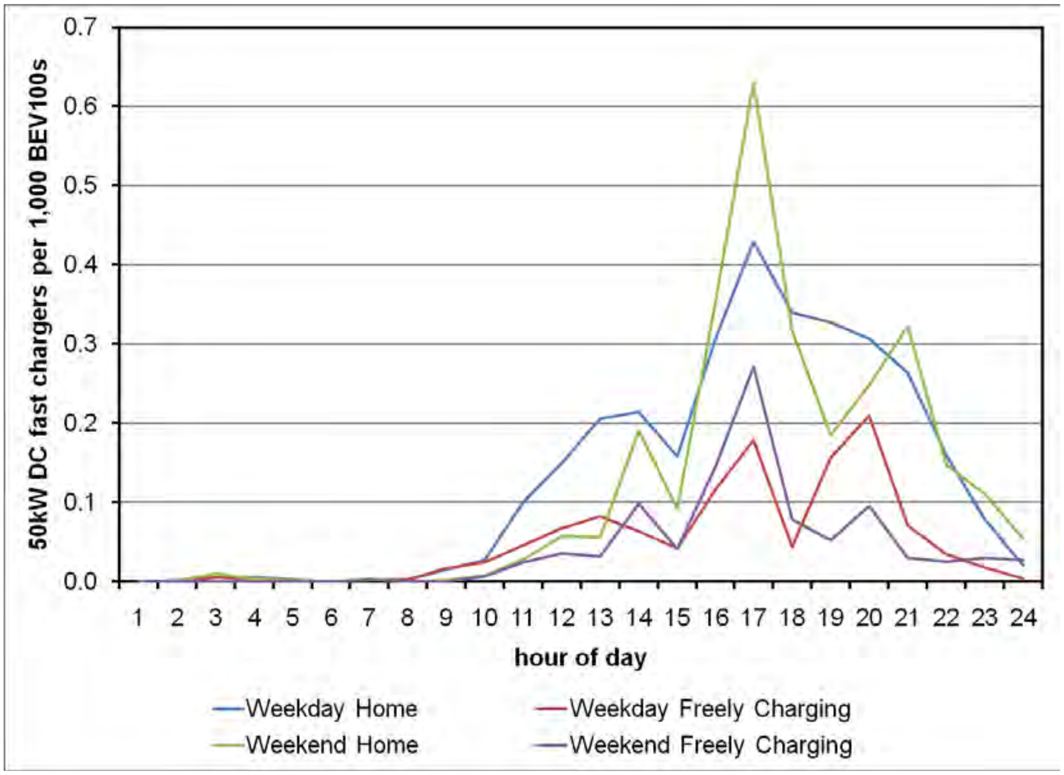


Figure 2-9
Case 3: 50kW DC Fast Charger use per 1,000 BEV100s

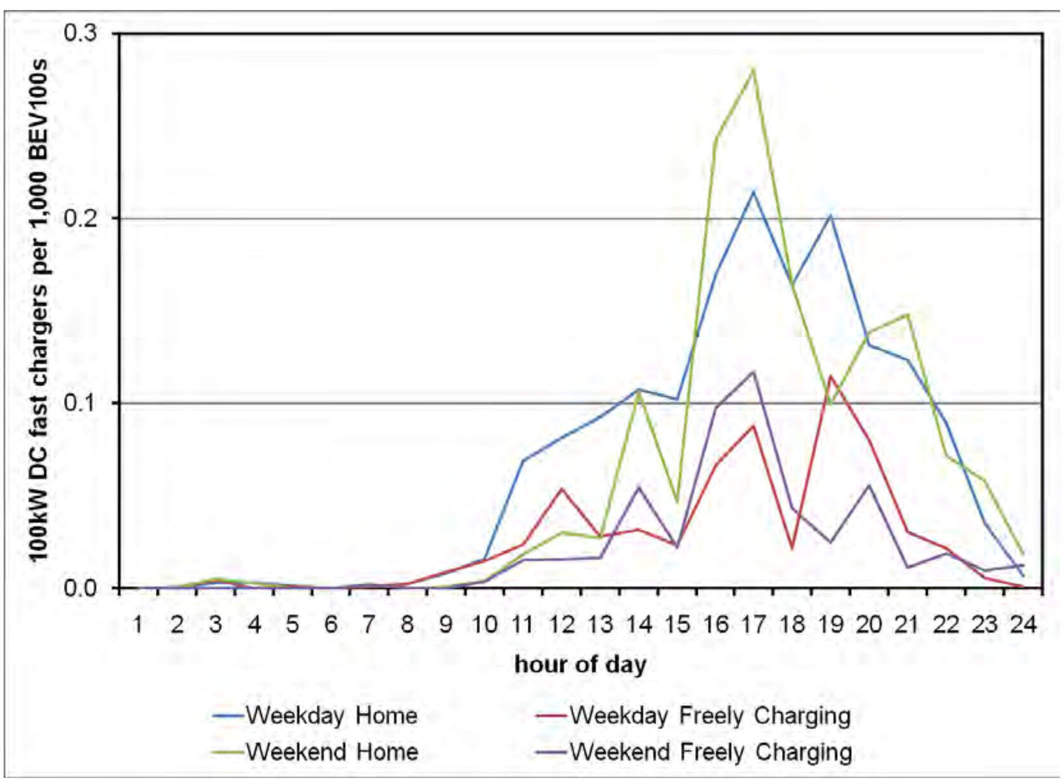


Figure 2-10
Case 3: 100kW DC Fast Charger use per 1,000 BEV100s

Table 2-3 summarizes the maximum charger use for Case 3.

Table 2-3
Summary of Case 3 results - maximum number of DC fast chargers in use for both weekdays and weekends

	50 kW	**100 kW**
Home Charging Only	1.1	1.0
Freely Charging	0.5	0.4

The simulation of the multi-car household provided the lowest DC charger usage results of any of the three cases. These also result in the largest amount of noise due to the small sample. It may be representative of many early adopters who purchase a BEV in a multi-car household.

Market Penetration Summary

The results of this analysis show that a limited number of DC fast chargers are needed on a wide-scale population basis. This model is limited in nature, as it does not provide geographic information, or behavioral responses to range and DC fast charging availability.

The three cases analyzed predict a maximum DC fast charger utilization of less than 5.2 per 1000 BEV 100s and dropping to a minimum of less than one per 1,000 BEV100s for case 3. This is lower than other estimates, and indicates that DC fast charging may have low utilization in the near term. There are likely to be regional variations from these national averages, but driving patterns tend to be consistent; a larger factor will likely be geographic location.

The difference in weekday and weekend driving behavior is less important than the amount of AC Level 2 charging infrastructure available to vehicles throughout the day. If these trips are common to a consumer, and it is known that a charger is not available at the destination, the owner may choose to purchase a different vehicle.

The effect of the rated charge power for the DC fast charger is another interesting outcome. The increased DC charge power of 100 kW nearly halves the number of DC fast chargers in use per 1,000 BEV100s -- due to decreased dwell times at the fast charger. In the near-term it is unlikely that 100 kW chargers will be installed, and 50 kW chargers will be the preferred unit. This is both due to cost and utility demand charges and regulations. Figure 2-11 and Figure 2-12 show the summary results from the analysis for both 50 and 100 kW, respectively.

In the near-term, DC fast chargers may find the highest utilization when placed on major transportation corridors between 75-150 miles away, such as San Francisco to Sacramento or New York to Philadelphia, where a reasonable number of BEVs are purchased and can be driven without excessive charging. This analysis shows one idea of the amount, and is intended to be indicative but not definitive.

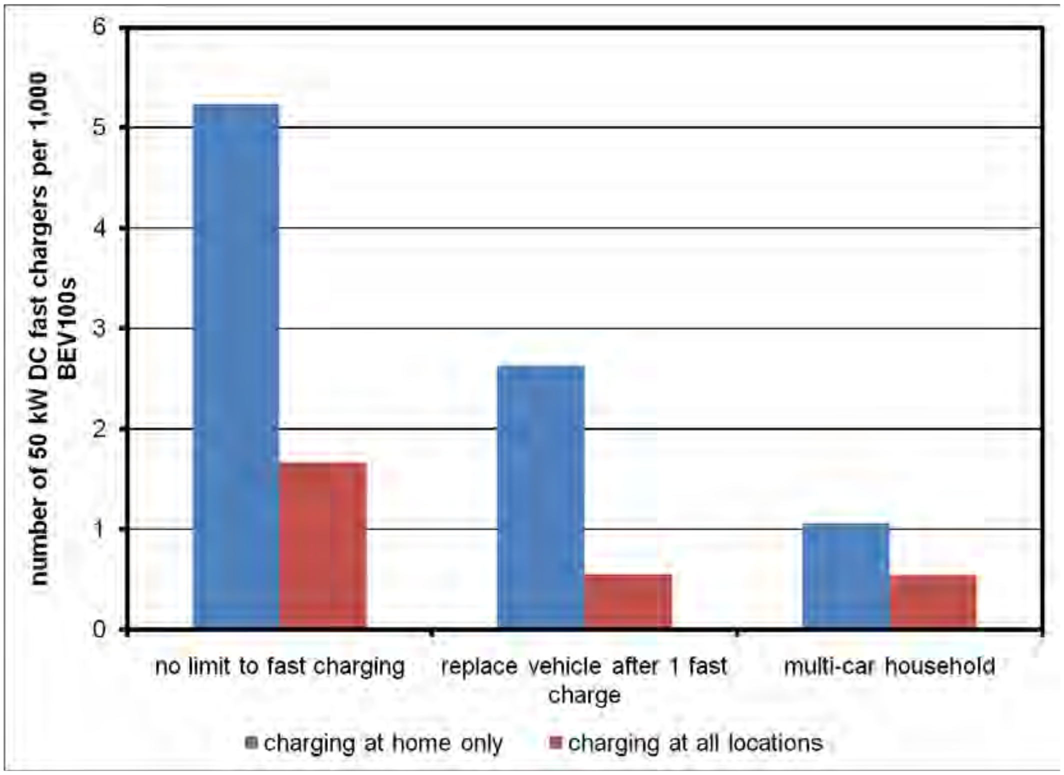


Figure 2-11
Maximum number of 50kW DC fast chargers per 1,000 BEV100s for all three cases

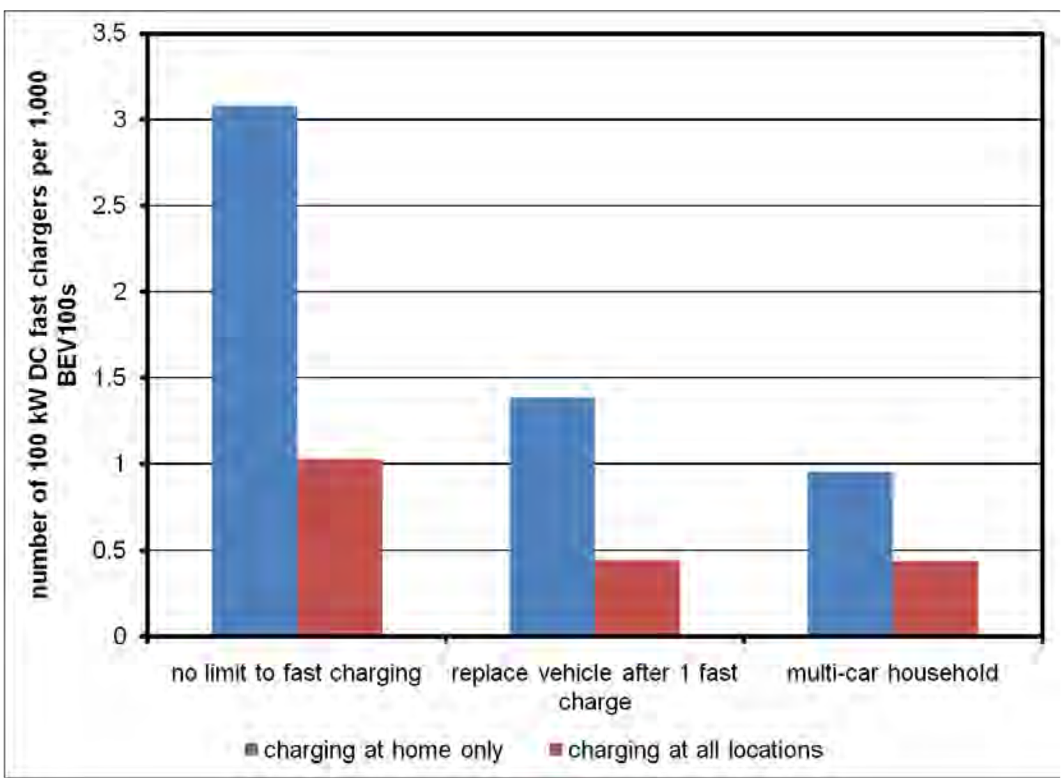


Figure 2-12
Maximum number of 100kW DC fast chargers per 1,000 BEV100s for all three cases

3
LEVEL 2 DC FAST CHARGER OPERATIONAL TESTING AND EVALUATION

Objective

As the penetration of DC fast chargers is expected to grow in the near future, it is important to evaluate the characteristics of these chargers to determine their impact on utility infrastructure and future vehicle-utility communication standards. Several key aspects need to be investigated including: efficiency, power factor, demand profile (which is also vehicle dependent), noise, and harmonic distortion.

A comprehensive evaluation of a DC fast charging system was undertaken. To this effect, a 200V, 3-phase system was acquired and installed at EPRI's facility in Knoxville, Tennessee. The unit was instrumented and the above mentioned parameters were investigated in detail. This and the following three chapters explain in detail this characterization effort.

Eaton's DC Quick Charger

EPRI has obtained an Eaton Level 2 DC quick Charging Station (Figure 3-1) that is currently under test at EPRI's laboratory in Knoxville, Tennessee. Key specifications of the charger are presented in Table 3-1. The charger is fed off a 208V, 3-phase supply. The Eaton charger uses the TEPCO/JARI CHAdeMO protocol.

The DC fast charger is fed from a 208 Vac 3phase source. The voltage at the input of the DC fast charger is 200 Vac after accounting for line voltage drop. The overall test setup schematic is shown in Figure 3-2. A description of the various sensors and data acquisition systems used as part of the test setup is provided in Table 3-2.

Figure 3-1
Eaton Level 2 DC Fat Charger (similar to the one under test)

Table 3-1
Eaton Level 2 DC Fast Charger Technical Specifications

Key Technical Specification	
Input voltage	200 Vac 3 phase/3 wire 50/60 Hz
Input rated current	168 A
Output voltage	400 Vdc
Output max current/power	125 A/ 50 kW
Charging station weight	Approximate weight 772lbs (350kg)
Charge Cable length	9 ft
Ground fault protection, 500mA	
Integrated over current protection	

Test Setup Overview

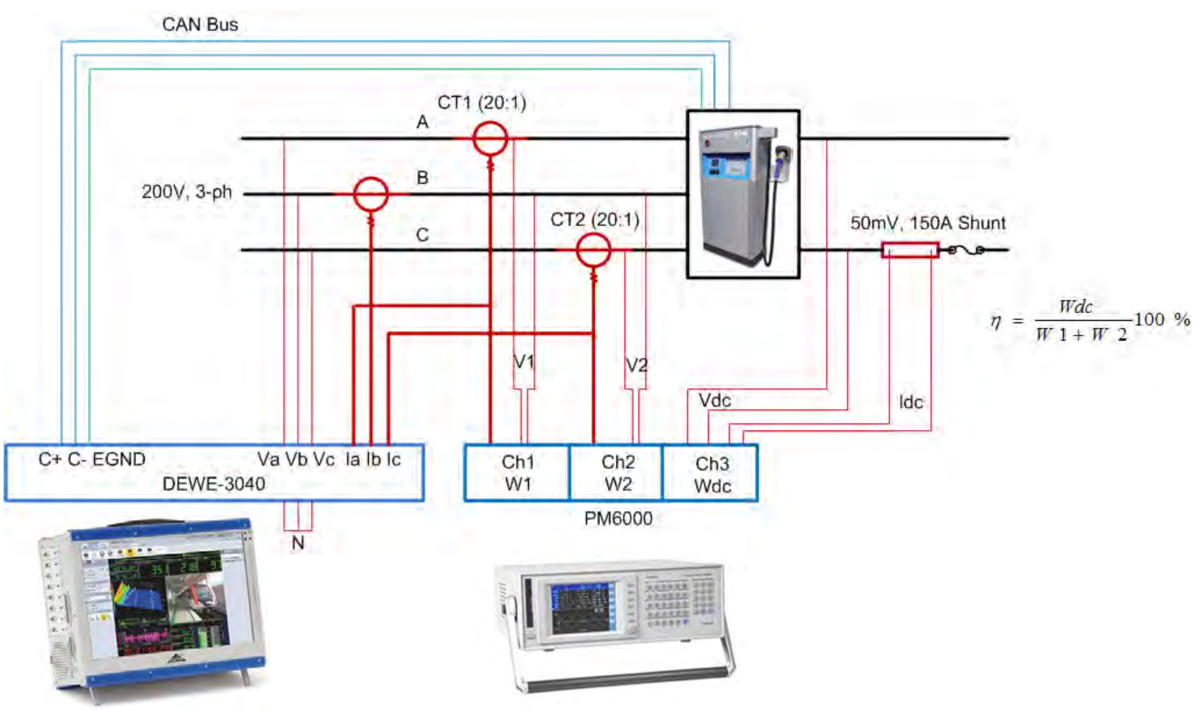


Figure 3-2
Level 2 DC Fast Charger Characterization Test Setup Schematic

Table 3-2 Test Data and Equipment

Key Technical Parameters	DAQ System Utilized
CAN Messages	Dewetron, Vector CANAnalyzer
Waveform data – V & I (AC &DC)	Dewitron
RMS data – V & I (AC &DC)	PM6000
Harmonic Data – V & I (AC &DC) (individual Harmonic Contents, Harmonic Distortion)	PM6000

Sensors

AC input measurement

Two line-line voltages (Vab and Vcb), all three line-neutral voltages (Van, Vbn, and Vcn), and all three line currents (Ia, Ib, and Ic) are recorded. For the purpose of measuring line-neutral voltages, an artificial neutral is created as the original system is a 3-phase 3-wire system. The voltages are directly acquired by the data acquisition/power measurement systems. Three 100:5A (20:1 ratio) current transducers (CTs) with an accuracy of 0.3% are used for measuring the input currents.

DC output measurement

The output DC voltage is directly measured by the data acquisition/power measurement system. A 50 mV, 150A current shunt is used for the DC current measurement.

Data Acquisition/Power Measurement

Power and Harmonic Measurement

A PM 6000 power analyzer is used to measure the input and output powers, the input voltage and current harmonic content upto the 30^{th} harmonic, the total input current and voltage THDs, and the input power factor. The meter has a basic accuracy of 0.02% of the reading and a bandwidth of 10 MHz. The two wattmeter method is used for the input power measurement. For this purpose, the voltages Vab, and Vcb, and the currents, Ia and Ic, are used.

Overall efficiency is calculated as

The data is written to an output file every 3.2 seconds.

Data Capture

In addition to power and harmonic measurement, all CAN bus messages between the vehicle and the charger as well as all voltage and current waveforms are captured using a Dewetron DEWE-3040 data acquisition system. The maximum sampling rate on the data acquisition system is 100 kHz.

Acquisition Rates and Test Data Validation

All voltages and currents are acquired at a 50 kHz sampling rate, unless specified differently in this document. The CAN messages are captured whenever they are transmitted, which is 100 ms for each message. All data captured by the PM 6000 is cross-validated with a Fluke 41B. All data captured using the DEWE-3040 is cross-validated using an oscilloscope.

Test Vehicles

Two test vehicles are used for the tests:

- Nissan Leaf (Figure 3-3)
- Mitsubishi i-MiEV (Figure 3-4)

Both vehicles are production variants and have a CHAdeMO-compliant Level 2 DC fast charging port. The battery specifications of both vehicles are shown in Table 3-3.

CHAdeMO DC CAN Bus Messaging

Under the CHAdeMO protocol, the vehicle is the master and the charger is the slave. The protocol uses CAN communication to transmit messages between the vehicle and the charger. The vehicle sets the current and voltage references, and controls the charging sequence. All CAN traffic is done through five messages, each transmitted every 100 ms. Three of these messages are allotted to the vehicle and two to the charger. Each message is 64 bits long and can carry several parameters. Table 3-4 lists the messages and their key contents. These messages can be monitored by any CAN tool in a “listen only” mode. In the present testing, the CAN bus messages are obtained through the DEWE-3040 as well as the Vector CANAnalyzer tool suite. A dbc file has been created for easy decoding and scaling of the signals.

Table 3-3
Test Vehicles and Battery Capacities

Vehicle	Battery Capacity (kWh)
Nissan Leaf	24
Mitsubishi i-MiEV	16

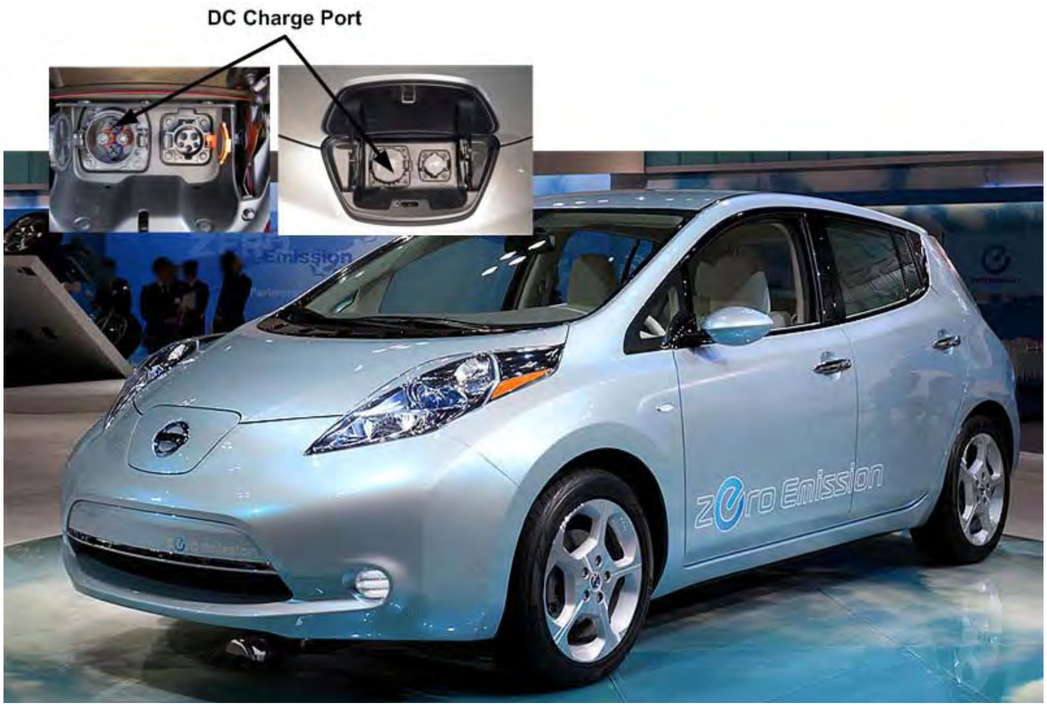


Figure 3-3
Nissan Leaf (Inset: CHAdeMO-compliant DC charge port)

Figure 3-4
Mitsubishi i-MiEV (Inset: CHAdeMO-compliant DC charge port)

Table 3-4
Key CHAdeMO CAN Bus Messages Monitored

Key Parameters Monitored
Total battery capacity
Maximum charging time
Target battery voltage and current
Remaining battery capacity
Present voltage
Present current

Instrumentation Summary

This chapter explains in detail the instrumentation test setup used for the data capture along with the test vehicles. The acquired data is post-processed in Excel/MATLAB and these results are presented in the subsequent chapters.

4
DC FAST CHARGER CHARACTERIZATION

Nissan Leaf Full Charge Characteristics

Figure 4-1 shows the remaining battery capacity obtained from the CAN bus and the charge profile while charging the Nissan Leaf from near empty (0.7 kWh). Figure 4-2 shows the corresponding DC voltage and current. The charge profile reveals that the complete charge cycle is divided into two regimes – a constant current (CC) portion where the charge current is held constant and a constant voltage (CV) mode where the DC voltage is held constant while the charge current ramps down. During the CC mode, the vehicle commands the DC fast charger to provide the requested current. Similarly during the CV mode, the vehicle commands the charge voltage to be held constant at the commanded value, while simultaneously setting the current reference.

Table 4-1 shows the key parameters of the Nissan Leaf charge cycle. Some key observations from this charge cycle are as follows:

- The DC charging stops when the battery capacity reaches 18 kWh (75% of total battery capacity). The total DC battery capacity charged is 18-0.7 = 17.3 kWh
- The actual DC energy expended during charging is 19.18 kWh. The additional energy is used by the vehicle's battery cooling and management system during the rapid charge cycle.
- The total time to charge was 32 minutes

Table 4-1
Nissan Leaf DC Full Charge Characteristics

	Total	Constant Current (CC) Mode	Constant Voltage (CV) Mode
Input AC energy (kWh)	21.3	13.2	8.1
Output DC energy (kWh)	19.2	11.8	7.4
Ending battery capacity (kWh)	18		
Battery capacity added during charge (kWh)	17.3		
Total charge time (minutes)	32		
DC Current during CC mode (A)	120		
DC voltage during CV mode (V)	395		

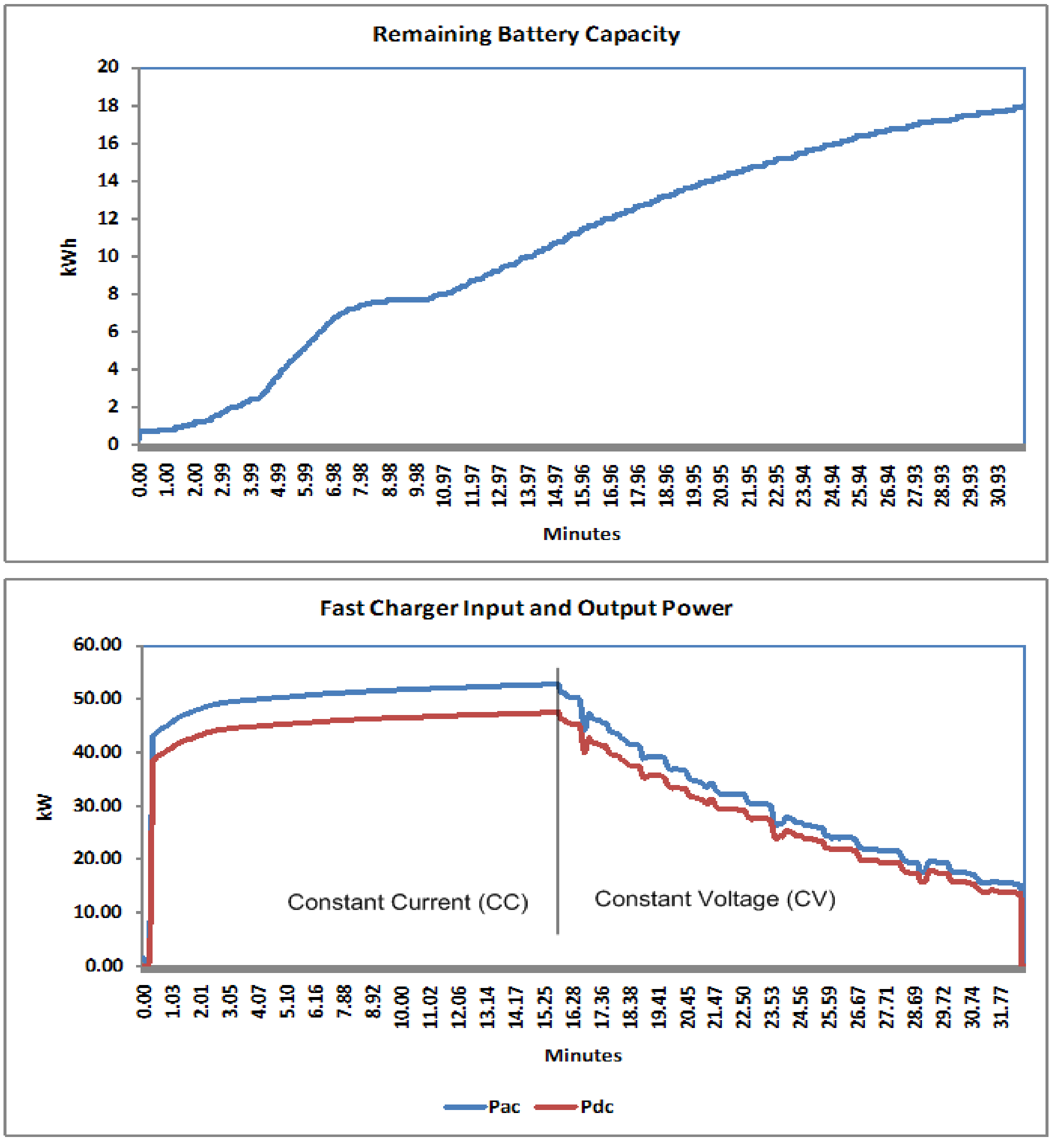


Figure 4-1
Nissan Leaf Remaining Battery Capacity (Top) and Charge Profile (Bottom) during Full Charge Cycle

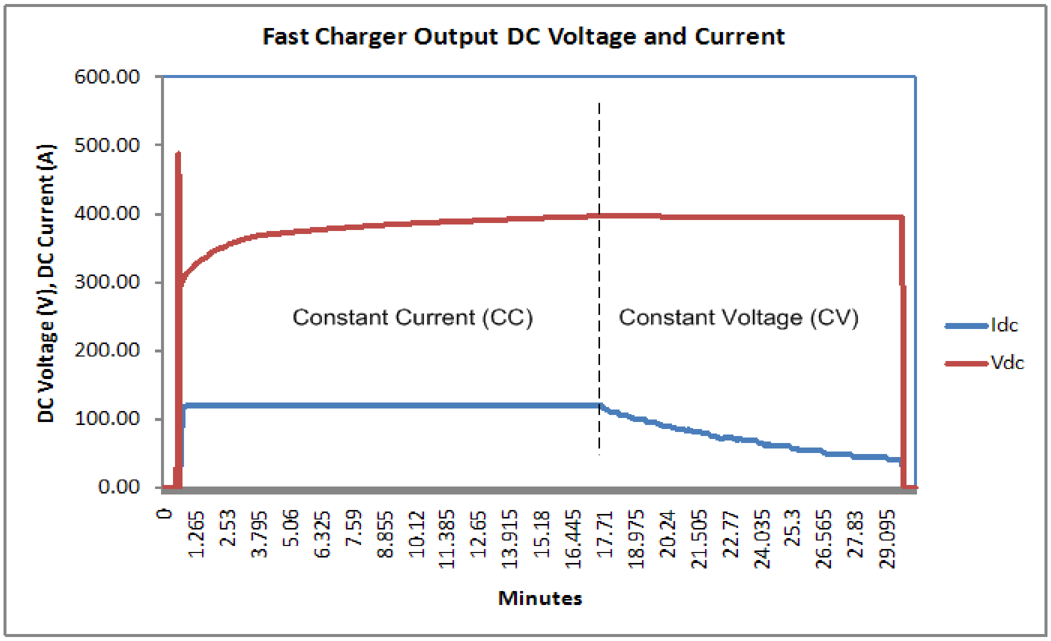


Figure 4-2
Nissan Leaf DC Current and Voltage during Full Charge Cycle

Mitsubishi i-MiEV Full Charge Characteristics

Figure 4-3 shows the charge profile while charging the Mitsubishi iMiev from near empty. Figure 4-4 shows the corresponding DC voltage and current. The charge profile reveals that the complete charge cycle is again divided into two regimes – a constant current (CC) portion where the charge current is held constant and a constant voltage (CV) mode where the DC voltage is held constant while the charge current ramps down. Table 4-2 shows the key parameters of the Mitsubishi iMiev charge cycle.

Table 4-2
Mitsubishi i-MiEV DC Full Charge Characteristics

	Total	Constant Current (CC) mode	Constant Voltage (CV) mode
Input AC energy (kWh)	10.5	4.2	6.3
Output DC energy (kWh)	9.4	3.7	5.7
Total charge time (minutes)	17		
DC Current during CC mode (A)	125		
DC voltage during CV mode (V)	361		

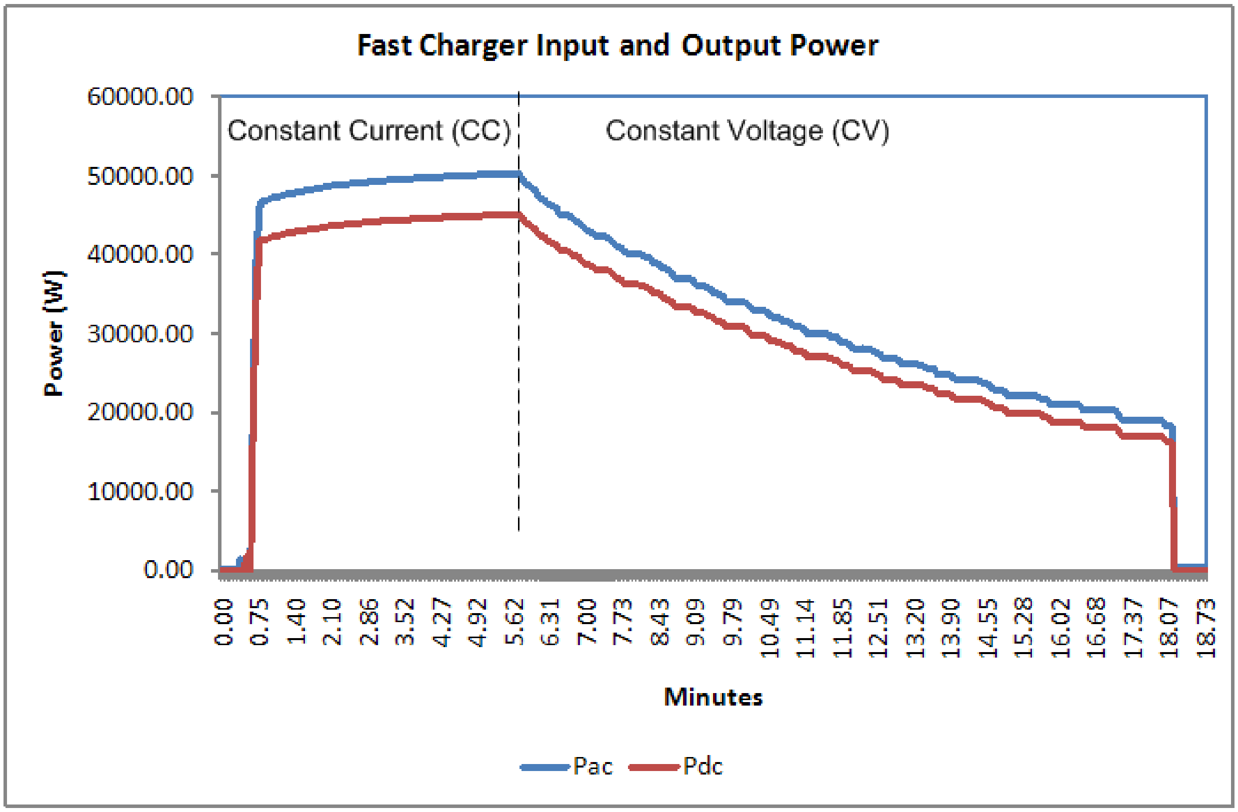


Figure 4-3
Mitsubishi iMieV Full Charge Profile

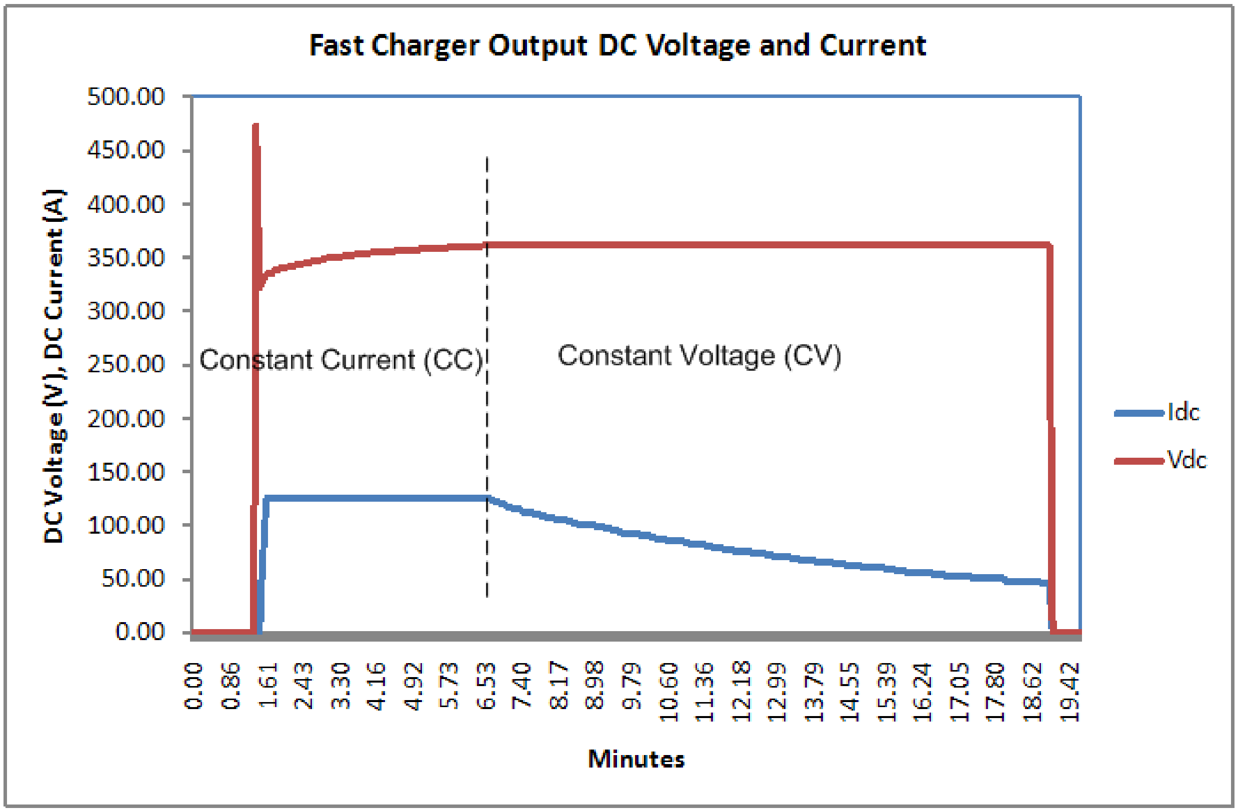
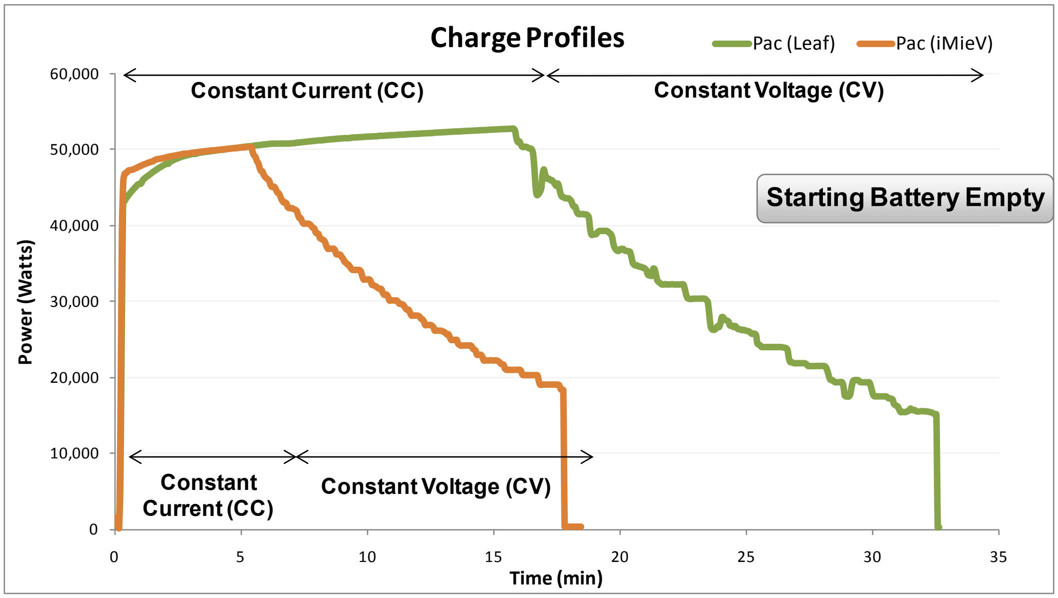


Figure 4-4
Mitsubishi iMieV DC Current and Voltage during Full Charge Cycle

Figure 4-5 provides full charge profile comparison between Nissan Leaf and Mitsubishi iMieV.



Eac(Leaf) = 21.28KWh **Eac(Leaf) = 13.15KWh** **Eac(Leaf) = 8.14KWh**

Eac(iMieV) = 10.47KWh **Eac(iMieV) = 4.16KWh** **Eac(iMieV) = 6.30KWh**

Figure 4-5
Full Charge Cycle Comparison between Nissan Leaf and Mitsubishi iMieV

Charging Behavior with Various Beginning Remaining Battery Capacities

Tests were carried out to investigate the charge time durations and behavior of the DC fast charger and the vehicle when beginning charging with various remaining battery capacities. Table 4-3 shows four different scenarios with the Nissan Leaf. The first scenario, starting battery charging from near empty (0.7 kWh), is assumed as the baseline case. Table 4-4 shows the total input and output energy from the DC fast charger and the energy consumed in the CC and CV modes. Figures 4-6 and 4-7 depict charge times and charge profiles for all the four cases. Key takeaways from this testing are:

- As battery charging is started from higher remaining battery capacities, rate of charging decreases. If charging is started with the battery already having 17.2 kWh, it takes 34 minutes to deliver 3.5 kWh of charge when compared to the baseline case (starting from 0.7 kWh) where 17.3 kWh of capacity is added in 32 minutes.
- True fast charging as in the baseline case is maintained as long as starting battery capacity is less than half of rated capacity.
- The ending battery capacity increases from 18 kWh to 20.8 kWh in the higher starting battery capacity scenarios.
- Figure 4-7 and Table 4-4 show that the CC mode decreases as the starting battery capacity increases. When started with 17.2 kWh already remaining in the battery, all charging is in the CV mode.

Table 4-3
Nissan Leaf Charging Characteristics with Various Starting Battery Capacities

Starting battery capacity (kWh)	Ending battery capacity (kWh)	Battery capacity added during charge (kWh)	Charge time (minutes)	Average charge rate (kWh/minute)
0.7	18	17.3	32	0.54
13.6	20.6	7	39	0.18
16.4	20.8	4.4	35	0.13
17.2	20.8	3.5	34	0.10

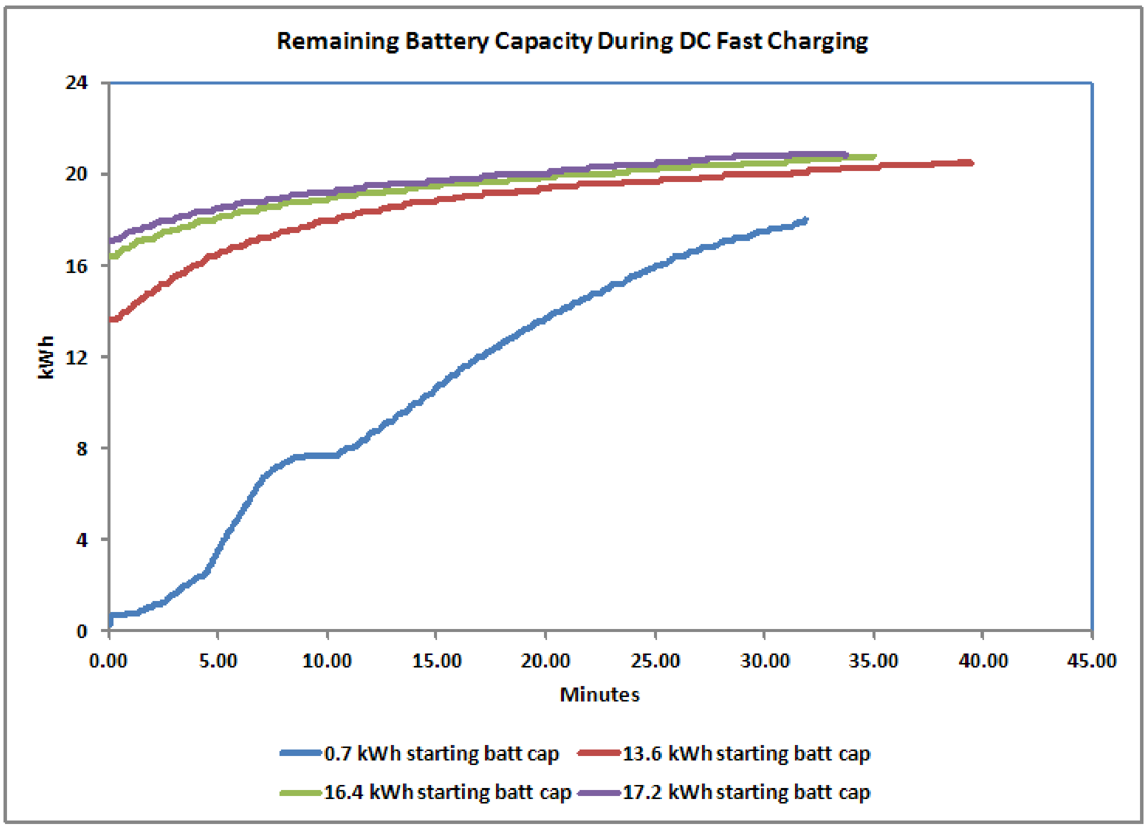


Figure 4-6
Nissan Leaf Remaining Battery Capacity for Various Starting Battery Capacities

Table 4-4
Energy Consumption for Various Starting Battery Capacity Scenarios (Nissan Leaf)

	Total		CC Region		CV Region	
Starting battery capacity (kWh)	Input AC energy (kWh)	Output DC energy (kWh)	Input AC energy (kWh)	Output DC energy (kWh)	Input AC energy (kWh)	Output DC energy (kWh)
0.7	21.3	19.2	13.2	11.8	8.1	7.4
13.6	8.6	7.5	1.3	1.2	7.3	6.3
16.4	6.0	5.1	0.3	0.3	5.7	4.8
17.2	4.4	3.7	-	-	4.4	3.7

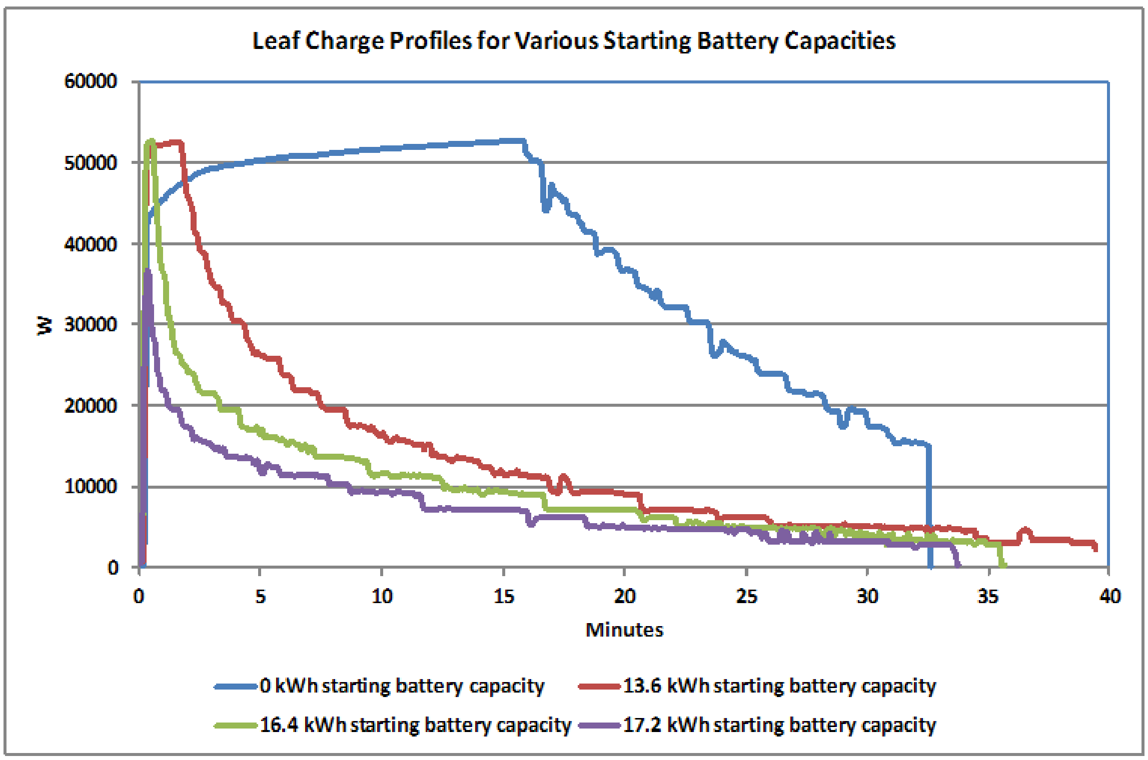


Figure 4-7
Nissan Leaf Charge Profiles for Various Starting Battery Capacities

Charge Time Comparison between Level 2 DC Fast Charging and Level 2 240V AC Charging When Starting With Partially Charged Batteries

The analysis in the previous section (reference Table 4-3) showed that the average charging rate (kWh/minute) decreased as DC charging was started with partially charged batteries. Further tests were conducted to compare the charge times between Level 2 DC fast charging and Level 2

AC charging when charging was started with batteries that were already partially charged. Two scenarios were picked – starting to charge with the vehicle battery already at 12 kWh and with the vehicle battery already at 16 kWh. All tests were conducted with the Nissan Leaf.

Table 4-5 shows the results of this testing. The charge profiles are shown in Figures 4-8 and 4-9 for the two cases respectively. From the results, it can be concluded that while the DC fast charging rate decreases as charging is started from higher remaining battery capacities, the total time to complete charge with the Level 2 DC fast charging is still significantly less than what it would take with a Level 2 240V AC charging.

Table 4-5
Energy Consumption and Charge Time Comparison Between Level 2 DC Fast Charging and Level 2 240V AC Charging for Various Starting Battery Capacity Scenarios (Nissan Leaf)

	Level 2 DC charging		Level 2 240V AC charging	
Starting battery capacity (kWh)	Input AC energy consumed (kWh)	Time to complete charge (minutes)	Input AC energy consumed (kWh)	Time to complete charge (minutes)
12	10.2	44	10.2	165
16	5.17	33	5.93	101

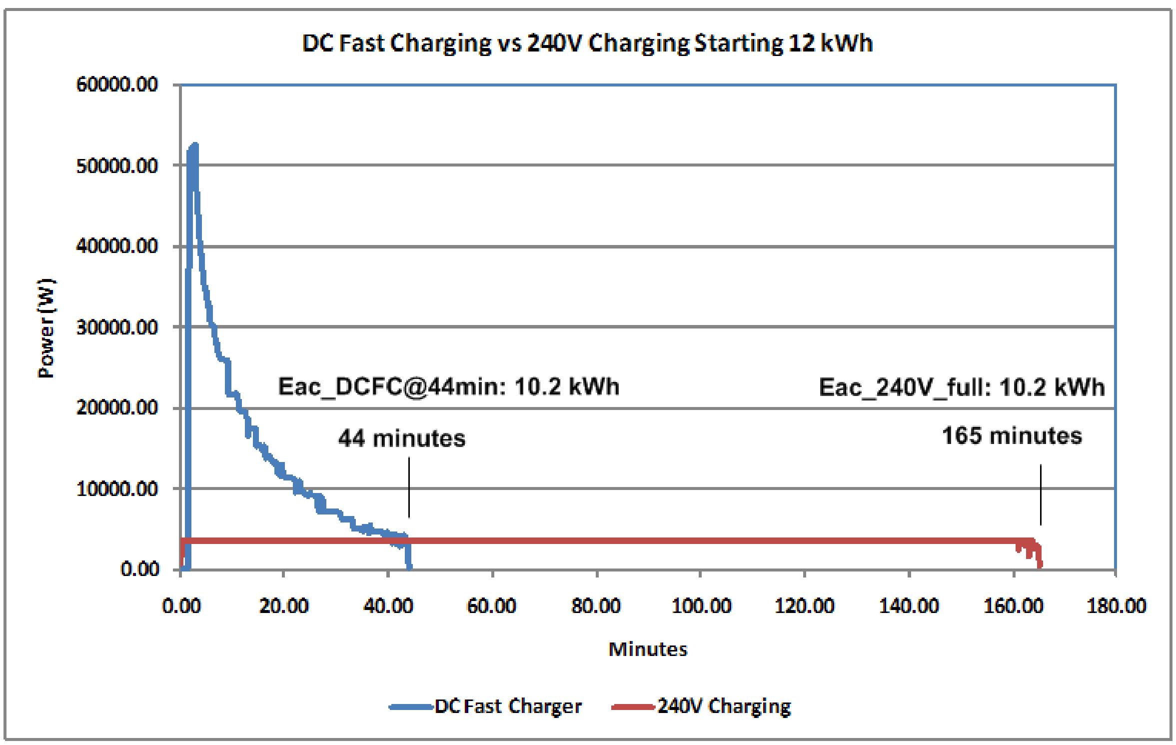


Figure 4-8
Level 2 DC Fast Charging and Level 2 240V AC Charge Profiles for Starting Battery Capacity of 12 kWh (Nissan Leaf)

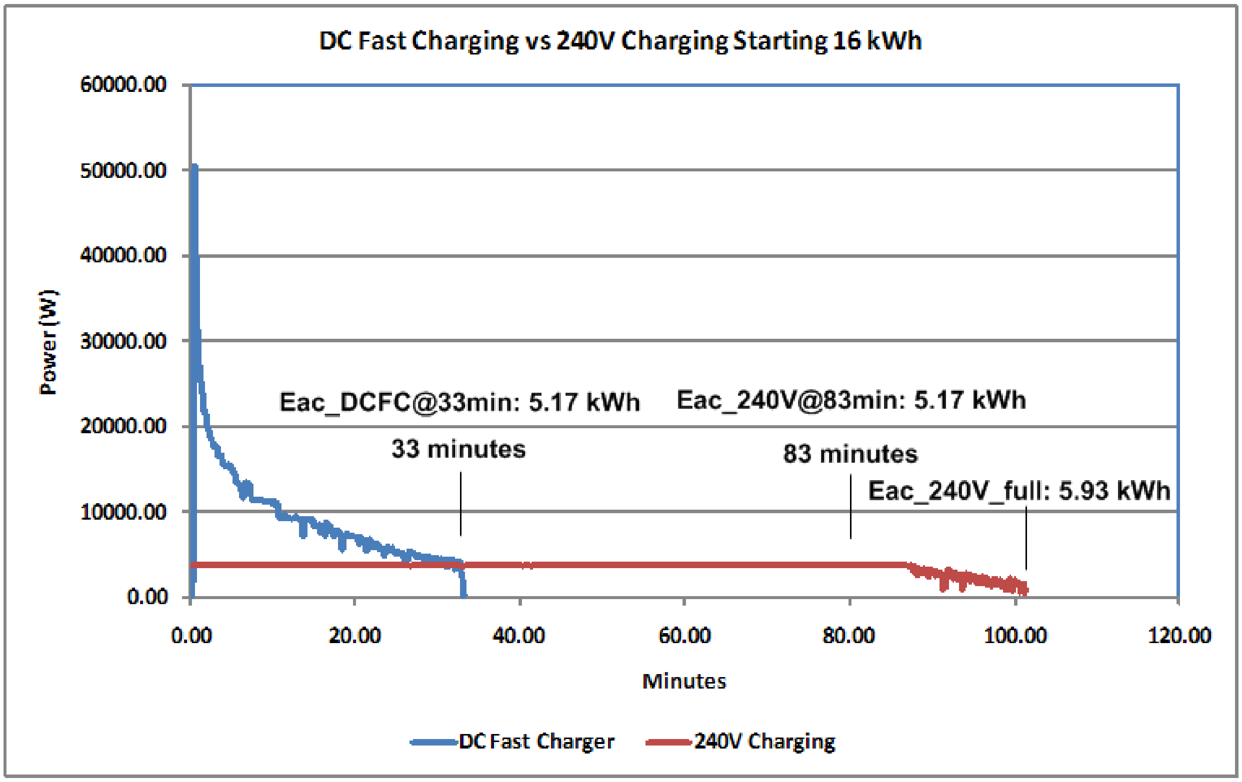


Figure 4-9
Level 2 DC Fast Charging and Level 2 240V AC Charge Profiles for Starting Battery Capacity of 16 kWh (Nissan Leaf)

CAN Message Signal Characteristics and Accuracy

The vehicle and the charger continuously interchange information including actual DC voltage and current over a CAN bus. This CAN bus data for a Nissan Leaf was monitored and the accuracy compared with data measured and acquired externally. Figures 4-10 and 4-11 show a comparison of the DC bus voltage current acquired over the CAN bus versus what was actually measured. It can be seen that both the data are in close agreement. This shows that the voltage, current, and other data transmitted over the CAN bus are accurate and can be reliably used for post-processing in lieu of measurement using external sensors.

Important information available from the CAN bus is the usable battery capacity of the vehicle and the remaining battery capacity of the vehicle. The latter has already been shown in Figures 4-1 through 4-5. Figure 4-12 shows the usable battery capacity broadcast by the Nissan Leaf's battery management system. When the DC fast charging is initiated, the vehicle first broadcasts the nameplate rating (in this case, 24 kWh). This quickly changes to usable battery capacity that is adjusted as charging progresses.

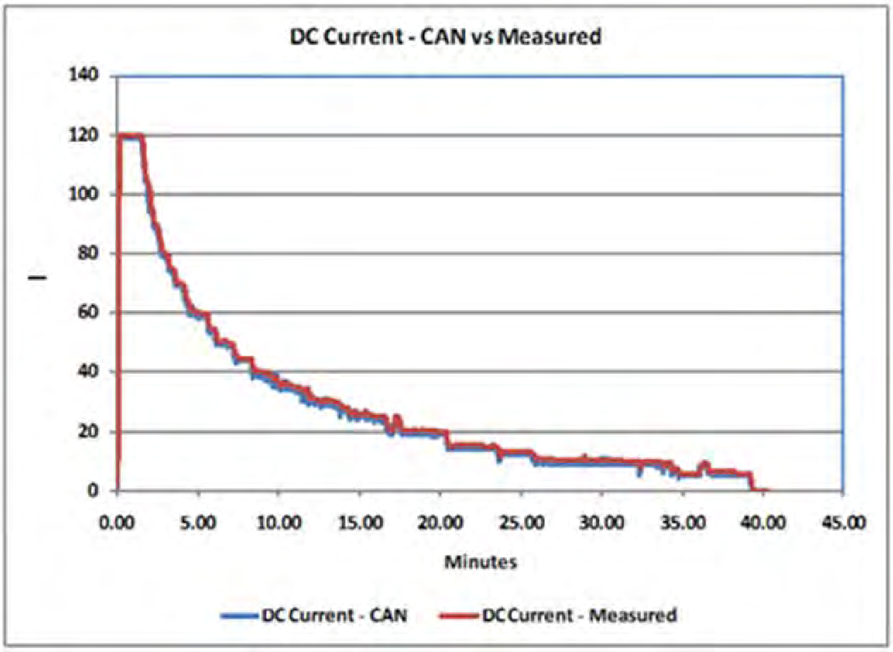


Figure 4-10
Comparison of Fast Charger DC Bus Current - Actual Measured and CAN Data (Nissan Leaf)

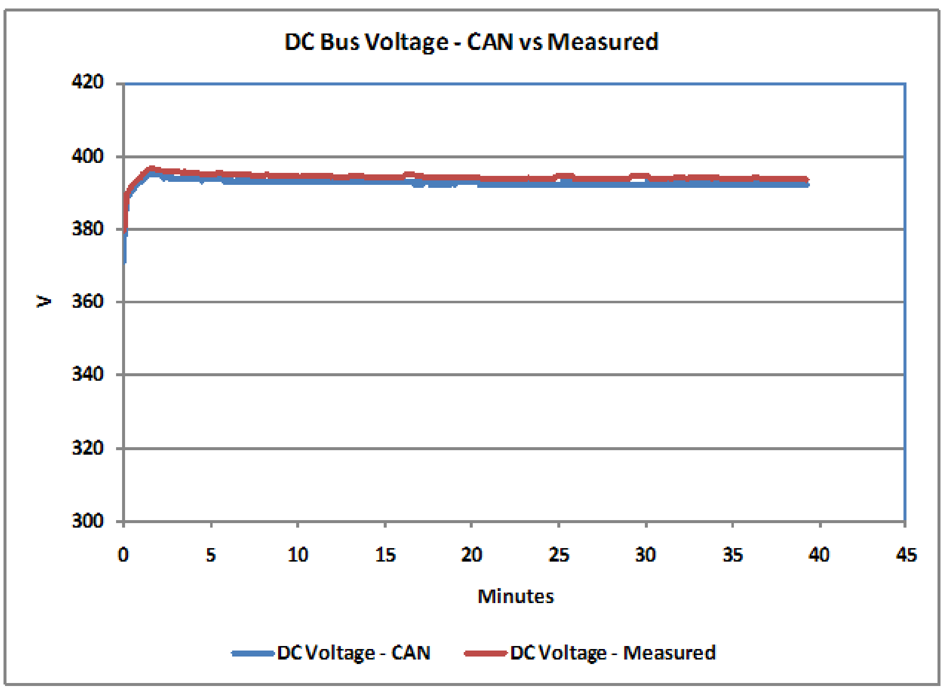


Figure 4-11
Comparison of Fast Charger DC Bus Voltage - Actual Measured and CAN Data (Nissan Leaf)

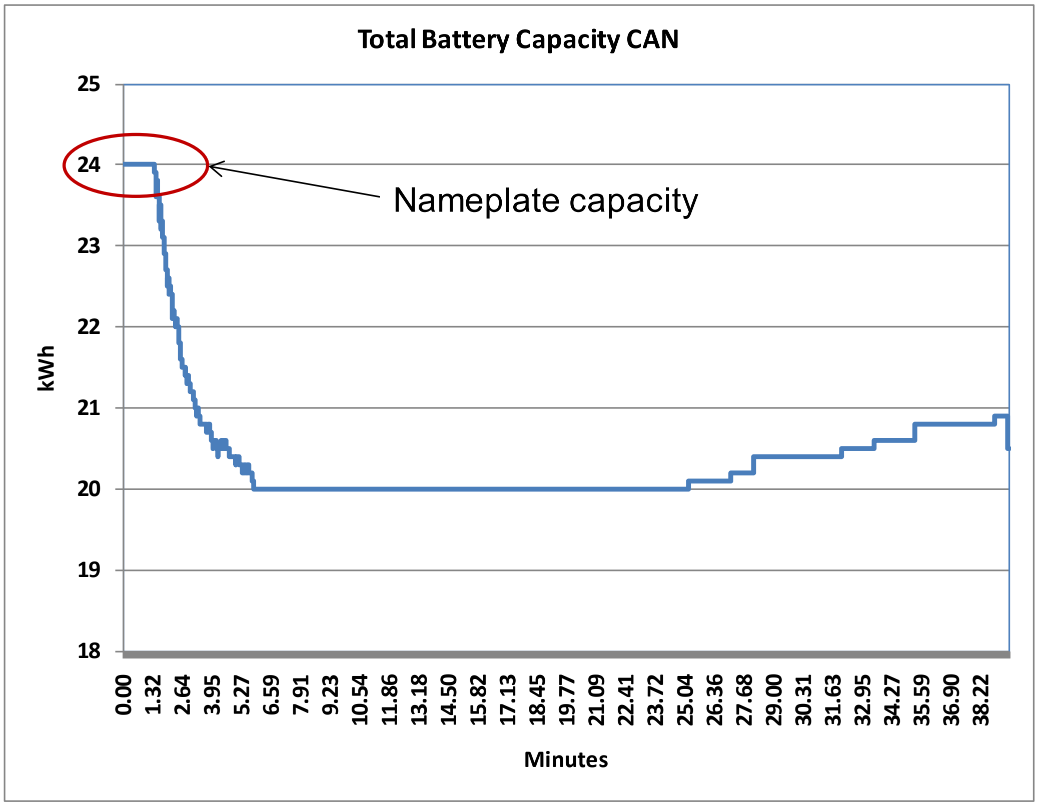


Figure 4-12
Usable Battery Capacity from CAN Data (Nissan Leaf)

Summary

The key takeaways are as follows:

- Full charge profiles (starting from near battery empty) for Nissan Leaf and Mitsubishi i-MiEV are recorded.
- The Nissan Leaf takes about 32 minutes and the Mitsubishi i-MiEV about 17 minutes for a complete charge (shown in Figure 4-5).
- The charge profile reveals that the complete charge cycle is divided into two regimes – a constant current (CC) portion where the charge current is held constant and a constant voltage (CV) mode where the DC voltage is held constant while the charge current ramps down.
- The DC energy consumed is slightly more than the actual energy added to the battery. This additional energy is probably consumed by the battery cooling and management systems on board the vehicle.
- Level 2 DC fast charging rate decreases as the starting battery capacity increases. For example, when started with a battery already having 17.2 kWh of charge, the Level 2 DC charging takes 34 minutes to add 3.5 kWh of energy to the battery.
- The CC mode decreases as the starting battery capacity increases. When started with 17.2 kWh already remaining in the battery, all charging is in the CV mode.

- Level 2 DC fast charging is faster than Level 2 240 V AC charging even when charging is started off with the battery already possessing significant charge.
- CAN bus messages are accurate and were compared with actual measured values.

5
EFFICIENCY AND POWER FACTOR

Efficiency

Efficiency of the power converter is calculated using the following formula

where Wac is the total three-phase AC input power and Wdc is the total DC output power. Figure 5-1 shows the efficiency of the DC fast charger versus its power rating (as a percentage of its rated load of 50 kW). It can be seen that the efficiency peaks around 50% rated power. This is very characteristic of power converters. In this case, the peak efficiency is about 90.5%. This efficiency can be expected to be slightly higher in 480 Vac systems due to decreased losses from the lower input AC currents that would be needed to achieve the same power as in the three-phase 208 Vac case.

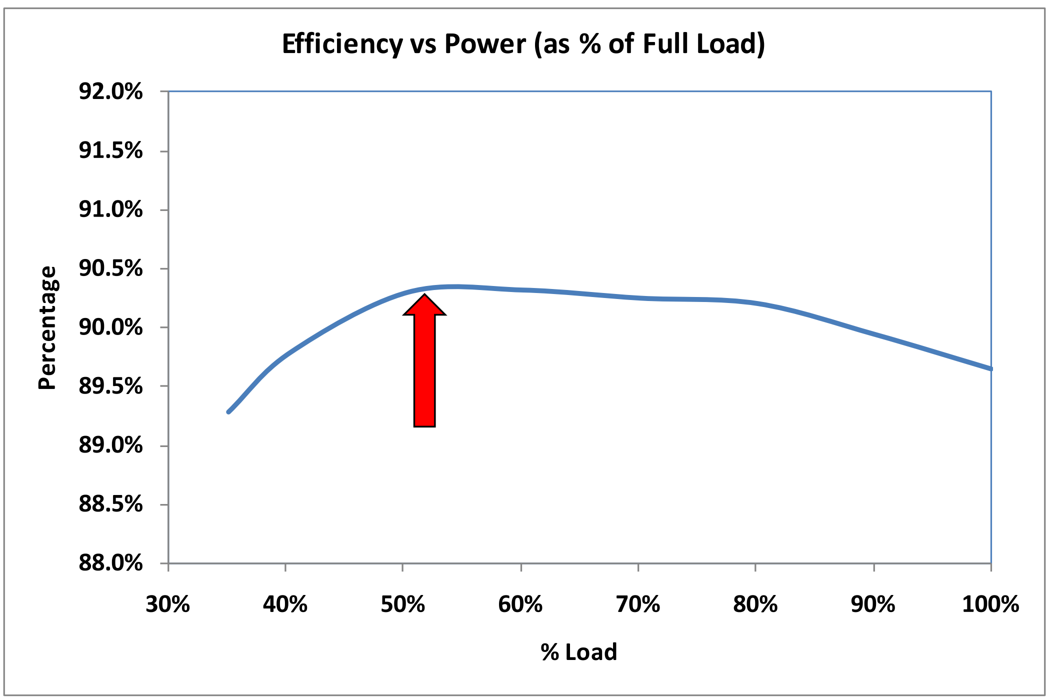


Figure 5-1
Efficiency vs Load as Measured for the Eaton Level 2 DC Fast Charger

Figures 5-2 and 5-3 show the efficiency plots during the entire charge cycle for the Nissan Leaf and the Mitsubishi i-MiEV. The efficiency during the constant current charge portion of the charge cycle is around 89.6%. Again, peak efficiency occurs at about 50% rated power, which happens somewhere in the constant voltage (CV) charge mode of the charging regime.

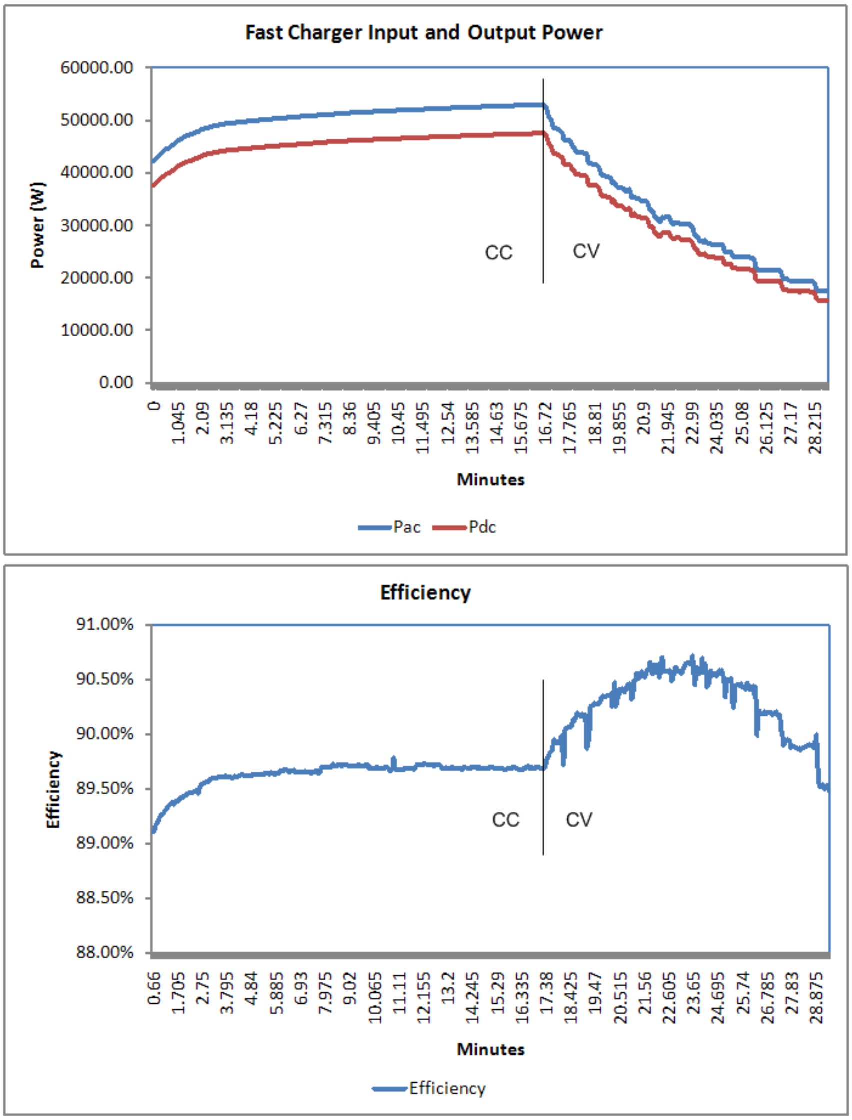


Figure 5-2
Nissan Leaf Input and Output Power Charge Profile and Associated DC Fast Charger Efficiency

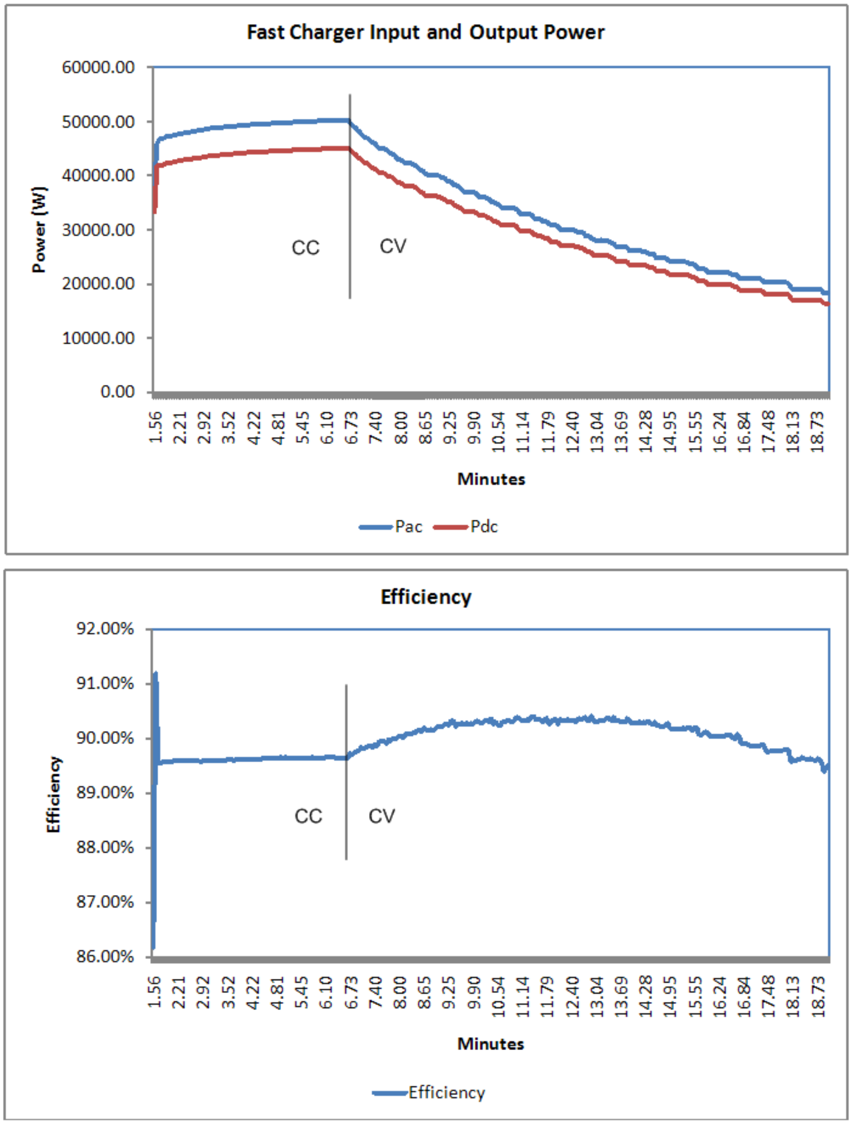


Figure 5-3
Mitsubishi i-MiEV Input and Output Power Charge Profile and Associated DC Fast Charger Efficiency

Power Factor

The power factor of the fast charger is close to unity (~ 0.99) for power output above 17 kW but drops rapidly below 17 kW. Figure 5-4 shows a plot of the fast charger power factor vs charger power in kW.

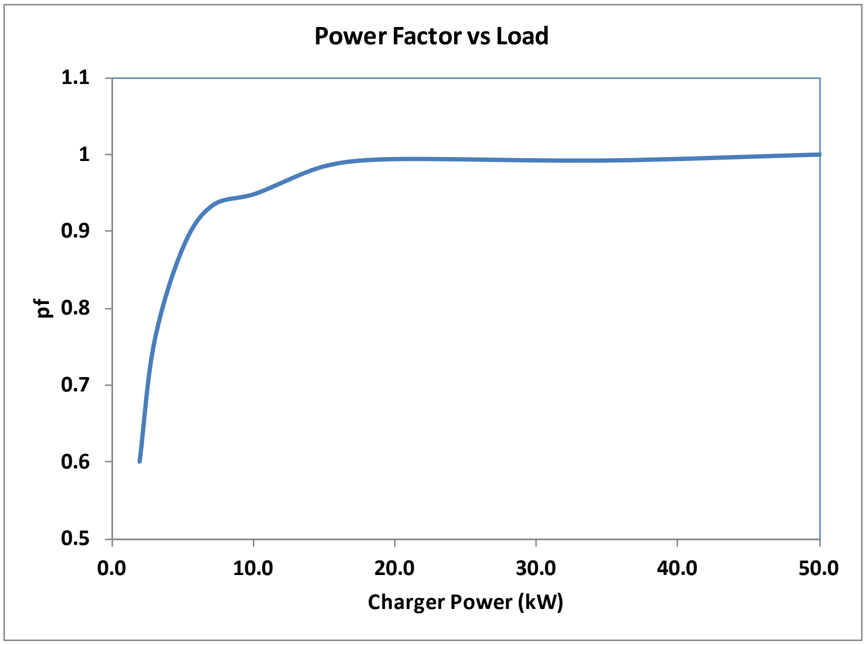


Figure 5-4
DC Fast Charger Power Factor vs Charger Power (in kW)

Summary

This chapter provides the experimental measurements for the Eaton Level 2 DC fast charger efficiency and power factor. Peak efficiency of the fast charger occurs at around half rated power and is around 90.5%. Efficiency during maximum power (that typically occurs when the DC fast charger is in the CC mode) is around 89.6%. Both these efficiencies can be expected to be slightly higher in 480 Vac DC fast chargers.

The Dc fast charger maintains unity power factor for power output greater than 17 kW. The power factor begins to fall when charger output power starts dropping below 17 kW.

6
HARMONIC ANALYSIS

Input AC Side Harmonic Analysis

The harmonic content of the input voltage and current of the Level 2 DC fast charger was captured using the PM6000. The Total Harmonic Distortion (THD) in the current (THDi) and in the voltage (THDv) as a percentage during the CC mode is presented in Table 6-1. Figure 6-1 and 6-2 show the voltage and current harmonic spectrums in the voltage and current at 53 kW (CC mode) and 20 kW (CV mode).

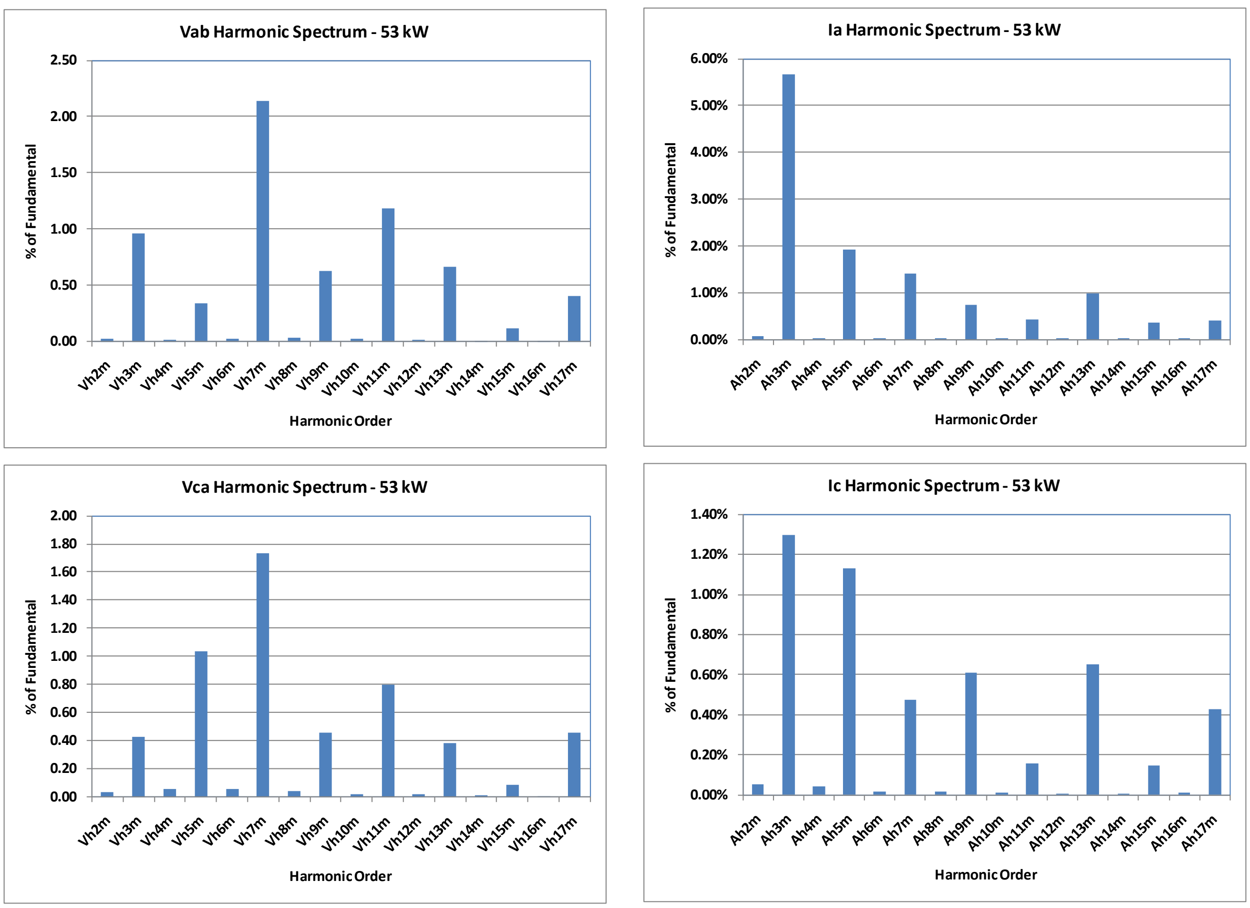


Figure 6-1
Voltage and Current Harmonic Spectrums at 53 kW (CC Mode)

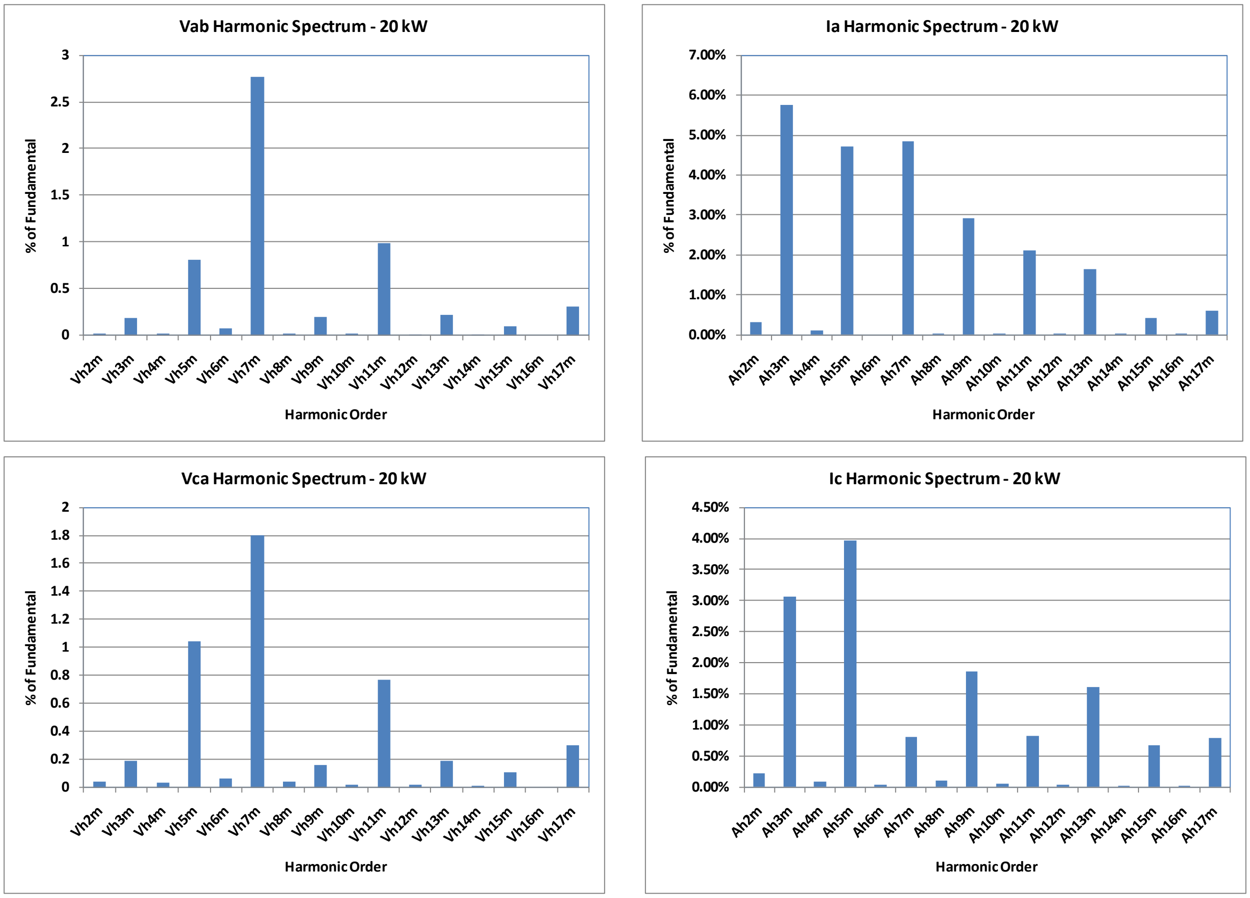


Figure 6-2
Voltage and Current Harmonic Spectrums at 20 kW (CV Mode)

Table 6-1
Voltage and Current THD with Level 2 DC Fast Charging (CC Mode)

THDv (%)	THDi (%)
1.45	6.3

The current spectrums indicate a significant 3rd harmonic component. This non-negligible 3rd harmonic probably arises from a single phase load such as a fan or an auxiliary power supply connected across two phases. Figures 6-3 and 6-4 show the variation of the 3rd, 5th, and 7th harmonic with power. It is important to note that the harmonic content of the three harmonics is highest at low loads and decreases as the load increases. Even though the 3rd harmonic is high only at low power levels, this can still cause potential problems on the distribution circuit especially if there are several other single phase loads with 3rd harmonic content. As the 3rd harmonic content simply aggregates from various loads, large penetrations of these chargers could contribute to potential problems. A detailed power quality simulation study is to underway to look at this particular issue.

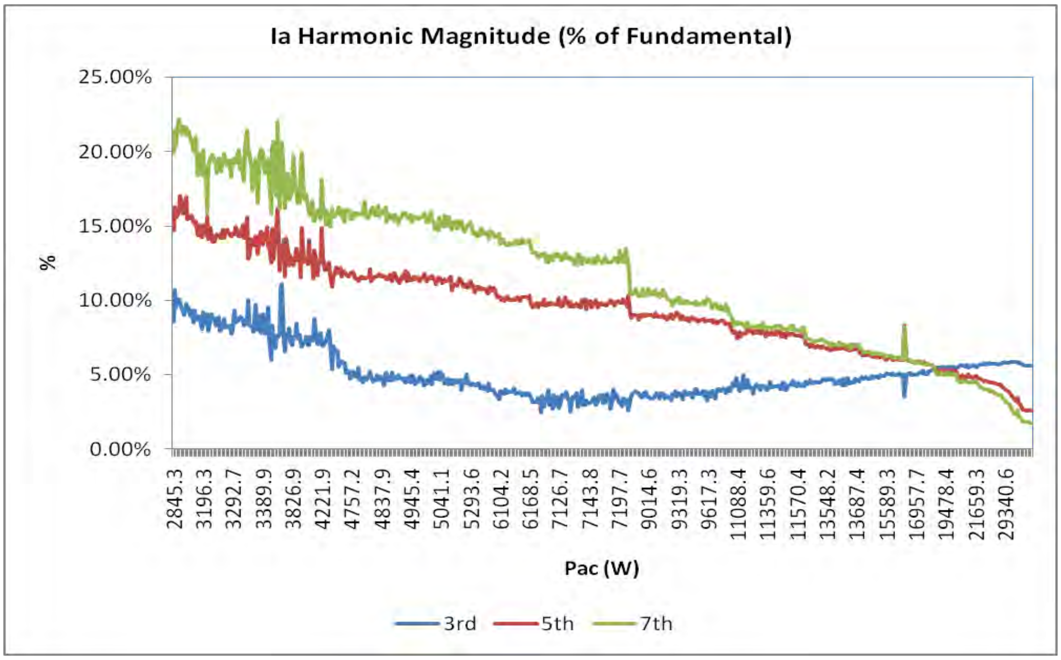


Figure 6-3
Variation of 3rd, 5th, and 7th harmonic in Ia with Charger Power

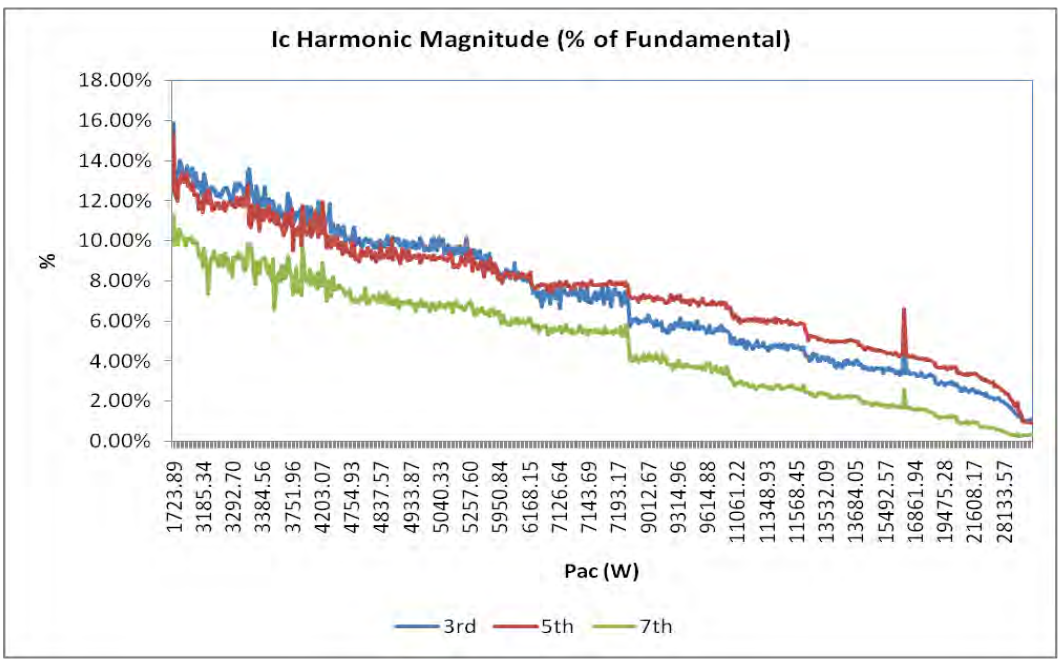


Figure 6-4
Variation of 3rd, 5th, and 7th harmonic in Ic with Charger Power

Output DC Side Spectral Analysis

The DC bus voltage and current were acquired at a 100 KHz sample rate. An 8192-point Fast Fourier transform (FFT) (Hanning window) is performed. Figures 6-5 and 6-6 show the FFTs of the DC voltage and current respectively. The spikes seen in the FFT could represent switching noise. These components are quite small (order of -70db) relative to the DC component. It is however very difficult to definitively attribute source of the frequencies to a particular power stage within the DC fast charger. It can be sufficiently concluded that the DC voltage and current have some switching noise component. This noise could be a potential source of interference for proposed PLC communications, especially narrowband technologies that operate at lower frequencies.

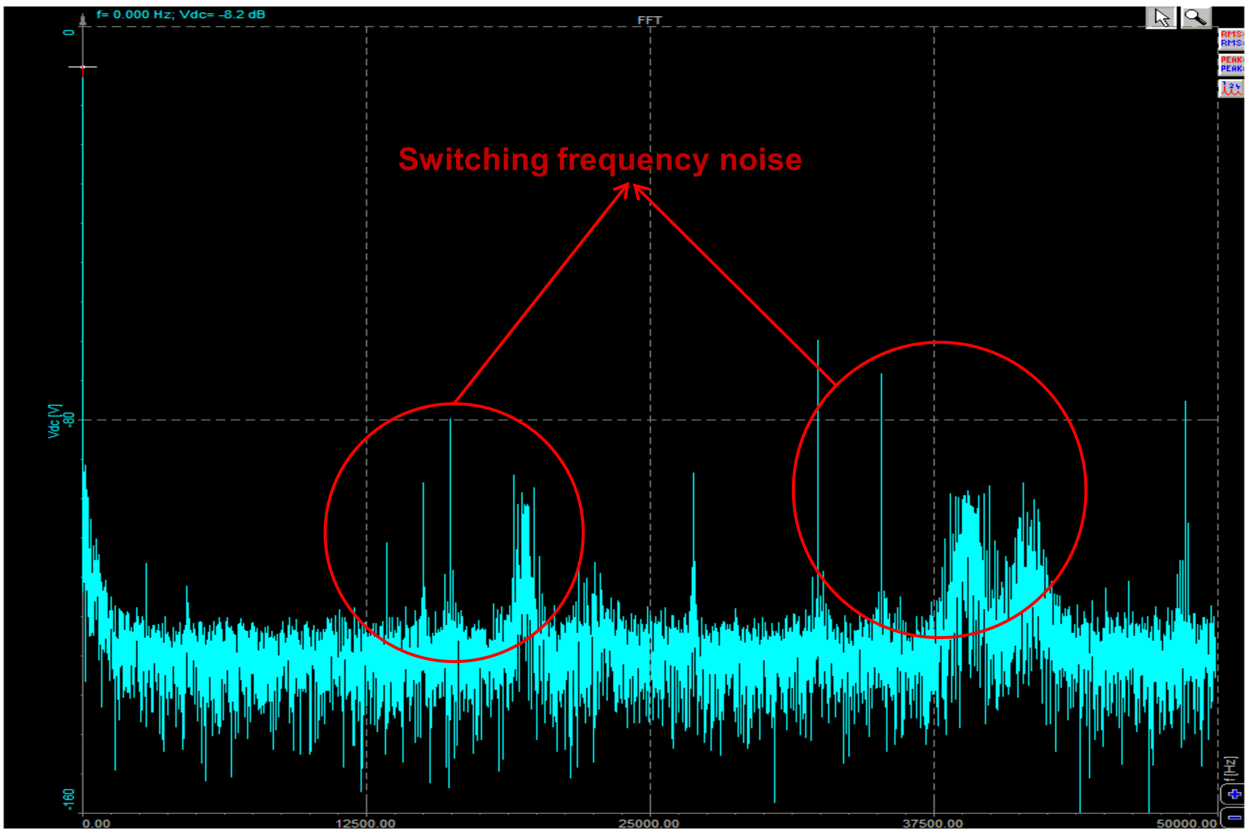


Figure 6-5
Output DC Voltage FFT; Frequency Range is from 0Hz at Left to 50,000Hz at Right

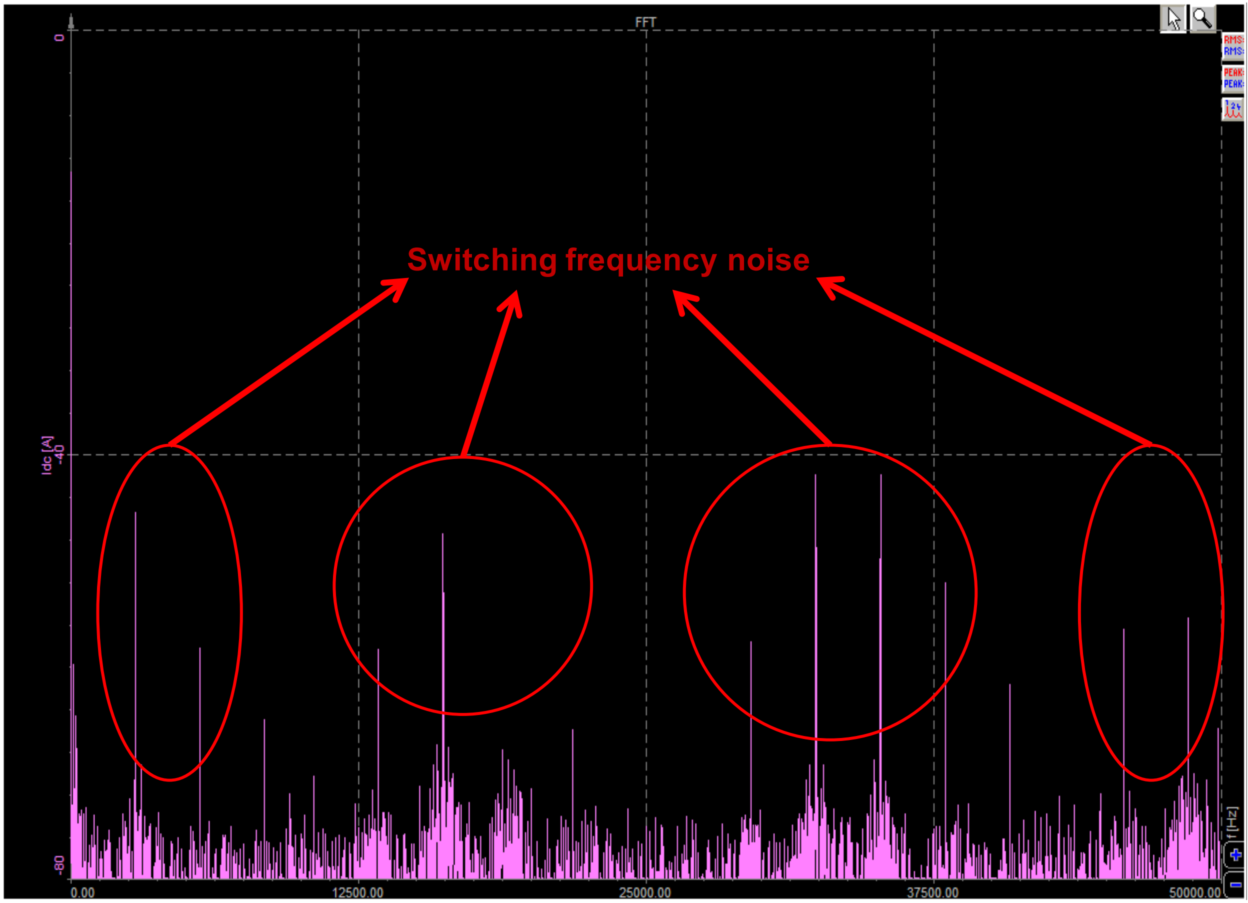


Figure 6-6
Output DC Current FFT; ; Frequency Range is from 0Hz at Left to 50,000Hz at Right

Summary

Key takeaways are as follows:

- The THD in either current or voltage is quite low during CC mode when the power factor is unity.
- The THD increases as charge power decreases.
- A non-negligible third-harmonic component is present, most probably from a single-phase auxiliary power supply or fan. EPRI will further investigate into this issue with other DC Fast charger manufacturers
- The DC voltage and current FFT reveal small switching frequency noise content that has the potential to interfere with future proposed PLC communication, especially low frequency narrowband technologies.

7 SUMMARY AND FUTURE WORK

Increased deployment of DC fast chargers is expected in the near future. The number of vehicles with DC fast charging capability is limited as of now but auto manufacturers have planned rollout of several new vehicles in the next 5 years. All level 2 DC fast chargers and vehicles with fast charging compatibility available today use the Japanese CHAdeMO protocol. Several companies have licensed this standard from TEPCO/JARI with plans to release DC fast chargers in the next few years. Simultaneously, the SAE is working on a proposed combo connector within the J1772 committee that can combine Level 2 AC as well as Level 2 DC charge connectors in one. At present, the CHAdeMO protocol requires the use of a separate connector for AC charging.

Modeling and analysis was done to study the potential for DC fast charger utilization. Results predict that relatively modest numbers of DC fast chargers (from 1 to 5 per 1000 BEV 100s) are needed to meet typical driving behavior needs.

A DC fast charger was instrumented and evaluated at EPRI's Knoxville, Tennessee laboratory. Detailed characterization of the DC fast charger was made. This included measurement of charge profiles (with various EVs), charging characteristics with various remaining battery capacities, efficiency, power factor, and input/output harmonics.

In 2012, EPRI plans to conduct additional testing with DC Fast chargers units that are listed to UL standards. EPRI will also test the 480V systems and compare the performance with 208V systems. EPRI is currently conducting a distribution impact study to understand the impacts of harmonics on distribution systems with combinations of DC fast chargers and AC level 2 chargers. That study and results will be included in a subsequent report.

Additional voltage and transient testing to be performed on the DC Fast charger system includes:

- Response to sags and swells – This test will subject the DC fast charger to input voltage sags and interruptions as per IEC 61000-4-34 and develop sag response curve. Vector types C and F (representing a L-L sag as well as a three-phase symmetrical sag) will be used to simulate the voltage sags. These tests will be conducted at several pre-selected battery SOCs to determine the effect (if any) of the BMS on the voltage sag ride-through. While the DC fast charger is not expected to ride-through voltage sag, this sequence of tests will evaluate how the fast charger responds to voltage sags and disturbances, will they automatically restart and where the re-charge start from, and what would be the delay between restarts.
- Response to inrush current – This test will characterize inrush current and calculate I^2t at all voltage sag and interruption points used in the sag response curve. The testing should include variations in sag duration, point on wave, and sag depth. Determine the worst case duration and point on wave for inrush into the fast charger. If the inrush trips any protection on the fast charger, note the conditions for which the event happens. This testing would determine whether inrush currents generated have the potential to cause system level disturbances,

whether start starts are needed, and if existing DC fast chargers are already equipped with such soft start mechanisms.

- Response to Long Term Sustained Under-Voltage and Over-Voltage – This test will verify DC fast charger response for long term (4 hours) for UV and OV. This test will also be done while the battery is charging as well as in charge sustaining mode to give a worst case.
- Response to oscillatory transients – Oscillatory transients occur when distribution capacitors are switched on to a distribution circuit. As well as creating momentary overvoltage situations these transients could cause resonance issues with equipment tied to this system. The purpose of this test is to characterize the fast charger response when subjected to 1.4 and 1.6 per unit (Open Circuit Voltage) oscillatory transients typical of capacitor-switching events.
- Response to impulse transients – Characterize the DC fast charger response when subjected to IEEE C62.41.2 Category B3 Combination Wave; if fast charger is confirmed to have surge protection then do multiple surges (100) with one-minute between each surge. For fast chargers that are not designed to meet the IEEE standard, the fast charger will be tested to the standard that it is designed to meet. For instance, if it is only designed to meet a 2kV for IEC 6100-4-5, then the unit shall be tested only to that standard. The hardware review of the fast charger should have revealed whether or not the fast charger contains surge protection. If the fast charger does not contain surge protection than 100 surges does not need to be done for each of the surge conditions. For fast charger which contains surge protection, the testing should determine the robustness of the protection and should be done with 100 surges in all case**.** If the fast charger does not indicate the level of surge protection designed to meet than test the device to the IEEE C62.41.2 Category B3 combo wave .
- Response to voltage notching – This test will characterize DC fast charger compatibility with an AC power source with moderate and severe voltage notching (multiple zero crossing)and other distortions.
- Grounding test **–** This test will characterize the response of the fast charger when the ground wire is broken prior to a charging event.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

1021743

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com