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Fast Charging: An In-Depth Look at Market Penetration, Charging Characteristics, and Advanced Technologies

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Abstract

Plug-in Electric Vehicles (PEVs) are now available in many North American and European markets, with more models expected to become available to consumers in the coming years. 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. In order to support PEV 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 and the infrastructure to support these fast charging systems. With a view to comprehensively understand the impact of DC fast charging on the customer as well as the electric utility, Electric Power Research Institute (EPRI) has been conducting detailed research into the market potential, technical capabilities, and installation costs. Demand charges and installation costs are currently the most significant barriers widespread adoption of fast charging. Creating a sustainable business case for fast charging will require economics that match utilization. This paper will discuss these findings in depth and will also provide an update on the status of DC fast charging related standards. With a view to address these shortcomings, EPRI has developed a direct medium-voltage fed all solid-state fast charging system, the Utility Direct Medium Voltage Fast Charger (UDFC). Such a system would allow the charging system to be connected directly to the medium voltage system, offer multiple ports so that total charging capacity can be intelligently shared between multiple vehicles at once, simplify installation and increase overall system efficiency. This paper will also present an overview of this concept and its benefits.

Keywords: Plug-in electric vehicles (PEVs), DC fast charger, CHAdeMO Connector, SAE Combo Connector, Battery Electric Vehicles (BEVs)

1 Introduction

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.

Fast charging requires high power. This presents unique challenges in terms of higher infrastructure cost, higher operational cost due to demand charges, and potential power quality impacts. Creating a sustainable business case for fast charging will require economics that match utilization. There will be approximately three levels of utilization:

- Low utilization Level – Initially, almost all sites will likely be low utilization. The economics of low-utilization sites will be dominated by two fixed costs: capital costs for equipment installation and demand charges
- Intermediate utilization Level – Intermediate-utilization charging happens once fast charging demand at one location is high enough that multiple ports can be profitably installed and total charging capacity can be shared between numbers of vehicles at once. At this level, the utilization will be high enough to offset the installation and fixed costs
- High utilization Level – High-utilization charging occurs once charging is common enough that fast charging is a customer expectation. This level will also support multi ports and controlled charging of number of vehicles at once

A comprehensive evaluation of commercial DC fast charging including development of advanced technologies to make them economically viable is presently underway at EPRI. This paper presents in detail some of the findings from this ongoing research.

2 DC Fast Charging Levels and Standards Overview

2.1 DC Charge levels

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).

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 (see Figure 1-1) 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 <= 100kW
  - 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

2.2 Status of DC Fast Charging

All public DC fast charger deployments in the North America, as of this writing, are based on protocols that have not been adopted as standards in the US. The hardware that has been fielded to date uses one of two protocols:

- CHAdeMO: A DC charging protocol developed and adopted as a standard in Japan; limited to approximately 50kW
- Tesla Supercharger: a proprietary protocol developed by Tesla Motors; 120kW

Approximately 200 CHAdeMO chargers have been deployed in the US, primarily through Department of Energy funded projects. Tesla has deployed eight Supercharger stations in the US, some with multiple fast chargers, with plans to deploy more than two dozen additional stations by late 2013. CHAdeMO fast charging station deployments continue both through DOE programs and through private and public efforts.

There are currently three production vehicles in the US market that accept DC fast charging: the Nissan Leaf and the Mitsubishi I, which both use the CHAdeMO protocol; and the Tesla Model S which uses Tesla's proprietary fast charge protocol. Approximately 27,000 Nissan Leafs, 1,500 Mitsubishi I and more than 10,000 Tesla vehicles are on the roads in the US, but the percentage of Nissan Leafs with a DC fast charge port was not available.

The Society of Automotive Engineers (SAE) continues to work to complete a US standard for DC fast charging. SAE has targeted publication of the new standards by the end of 2013. The SAE work is detailed in the next section of this document on protocols. General Motors (GM) is expected to introduce the first vehicle in the US that uses the new SAE Combo connector/fast charging standard, the Chevy Spark EV, sales of which began on June 25 of this year in California. Till date two vendors have made public announcements about field testing of the SAE Combo DC fast charge standard and it is expected that chargers listed to UL standards will be available before the end of 2013.

It is expected that the US will have a combination of all three DC charging protocols discussed for the foreseeable future. Nissan and Mitsubishi continue to sell vehicles equipped with the CHAdeMO interface and have not announced plans related to adoption of the SAE Combo standard. Nissan, in order to support wider deployment of DC fast charging, has actively been selling a low cost CHAdeMO fast charger in the US. Tesla has stated that Model S owners will have lifetime free access to their supercharger network and has not indicated that it will adopt the SAE standard. Given the physical, control and power level differences across these DC charging protocols, developing adapters for consumer use will be a difficult and cost prohibitive challenge.

Several electric vehicle supply equipment vendors have indicated that they will offer dual port DC fast chargers that provide both a CHAdeMO and Combo connector interface. For entities seeking to deploy charging stations in 2013, a critical decision will be whether to deploy CHAdeMO charging stations or to wait until late in 2013 when dual port charging stations become available.

While most DC fast chargers deployed to date have a 50kW capacity, several vendors have shown products that operate at reduced (10kW, 25kW, etc…) power levels. This may be a source of confusion for consumers where charge times for equipment labeled as a "DC fast charger" will not be consistent.

2.3 DC Fast Charger Standards

SAE DC Fast Charge Standard

SAE has labeled their DC fast charging connector the "combo" connector. The design combines the physical pin-out and structure of the SAE J1772 AC connector with two added high current DC power pins. Low level control signaling is based on use of "pilot" and "proximity" wires in the interface. High level control communications is based on use of a power line carrier (PLC) communications technology called HomePlug GreenPHY (HPGP). SAE standards define the messaging for charger control. Europe has also adopted a variation of the combo connector which combines the European AC charging connector with added high current DC pins. The connectors are physically sized so that the same size fuel port door can be used on vehicles independent of the connector type (SAE combo or European combo). This allows use of common sheet metal components for vehicles that are sold in both the US and Europe.

SAE Combo Vehicle Side Receptacle

SAE Combo Charger Side Plug

Figure 1: SAE Combo Connector

There are a number of SAE standards that define the full DC charger interface, and include:

- SAE J1772 – defines electrical signaling, pin out, connectors, receptacles, and signal timing for both AC and DC charging
- SAE J2847/2 – defines the communications messaging for DC charger control
- SAE J2931 – defines the requirements and communications technology for AC and DC charger control

Draft versions of each of these standards have been published. Efforts are underway within SAE to coordinate finalized versions of the various parts of the standards while also attempting to align functionality with international standards work being carried out by the International Standards Organization (ISO) and the International Electrotechnical Committee (IEC). A DC charger control standard developed in Germany (DIN 70121) has been used as the model and basis for command and control of the DC charger interface in both the SAE and ISO/IEC efforts. ISO/IEC has undertaken an update of DIN 70121 which has impacted finalizing the SAE work.

Several vendors are actively producing the SAE combo connectors that are certified to UL standards.

CHAdeMO Protocol

This is the Japanese standard for DC fast charging. While it has not been recognized in the US by any national standards body, nearly the entire public fast charging infrastructure deployed in the US is based on this protocol. Vendors that wish to make CHAdeMO products must become members of the CHAdeMO association and license the protocol.

CHAdeMO Vehicle Side Receptacle

CHAdeMO Charger Side Plug

Figure 2: CHAdeMO Connector

Tesla Supercharger Protocol

The Tesla Supercharger protocol uses a proprietary connector/plug combination and a proprietary control scheme. The system is rated at up to 120kW. To date, Tesla has not published detailed information on the protocol and has publically stated that their systems are designed to support only their own products for the foreseeable future.

3 DC Market Penetration

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 can be used to both model charging behaviors as well as understand everyday driving behaviors.

Figure 3 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 was not driven. 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.

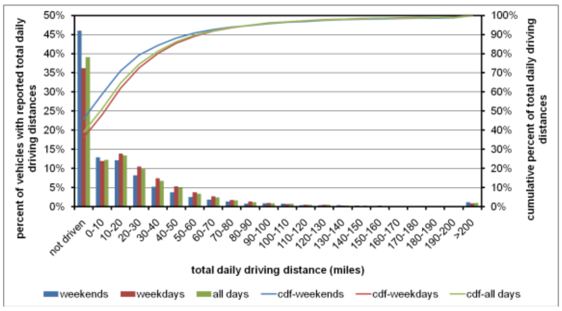

Figure 3: Distribution of day type driving behavior (Source: 2009 NHTS)

Three cases were 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. This analysis provides an order-of-magnitude result as to the actual need of DC fast charging based on average daily driving behavors.

3.1 Market Penetration Summary

Results from the three cases 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. 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 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 or lower power chargers like 20KW, 25KW or 44KW chargers will be the preferred unit. This is both due to cost and utility demand charges and regulations.

Figure 4 show the summary results from the analysis for 50 kW. In the near-term, DC fast chargers will likely need to be placed in major transportation corridors between 75-150 miles away, such as San Francisco to Sacramento or New York to Philadelphia or Knoxville to Chattannoga, where a reasonable number of BEVs are purchased and can be driven without excessive charging.

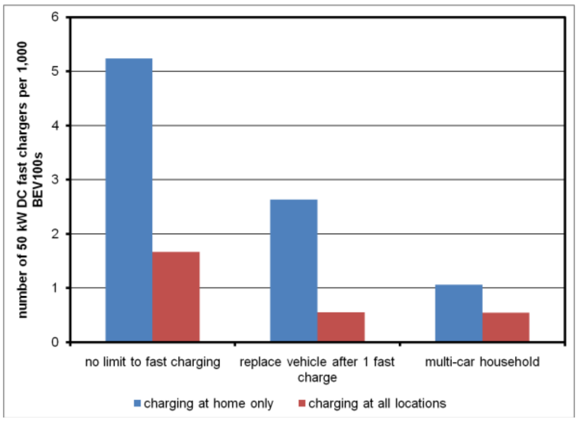

Figure 4: Maximum number of 50kW DC fast chargers per 1,000 BEV100s for all three cases

4 DC Fast Charger System Characterization

4.1 Commercial DC Quick Systems

Commercially available DC fast chargers are all low-voltage 3-phase input units that can be supplied off 208/480 V AC. These DC fast chargers require conventional three-phase transformers that convert medium voltages (~15 kV L-L) to the required lower AC voltage. All together, a conventional DC fast charger has the following power conversion stages:

- AC-AC stage (3-phase distribution transformer 15 kV → 480 V AC)
- AC-DC power electronic stage (the first stage within the DC fast charger that converts 480 V AC into an intermediate DC voltage)
- DC-DC power electronic stage (the second and last stage of the DC fast charger that converts the intermediate DC voltage to the voltage required to charge the electric vehicle (EV) battery)

At low voltages, the input current is typically large, 90A at 480Vac or 200 A at 208 V AC, resulting in increased losses and lower efficiency. Most DC fast chargers have efficiency in the 90-92% range.

4.2 Testing and Characterization

A detailed understanding of DC fast charging characteristics is needed to evaluate the impact of these systems on the distribution system as well as to understand how these would serve the customer. While more and more DC fast chargers are arriving on the market, their actual performance in terms of charge profiles and durations, efficiency, and power quality (harmonics, total harmonic distortion, etc.) are still unknown. Further, some of these characteristics such as the harmonic quality are closely dependent on the DC fast charger power.

This paper documents the characterization results from one 200V Eaton DC Level 2 charger. The charger uses the TEPCO/JARI CHAdeMO protocol. This system was tested at EPRI's Knoxville facility. Based on comprehensive testing, it was observed that full charge from near empty battery took about 32 minutes for a Nissan Leaf and about 17 minutes for a Mitsubishi i-MiEV. This is illustrated in Figure 5. The two vehicles differ in battery capacity, with 24 kWh and 16 kWh respectively. The charge profile comprised of two regions – a constant current portion (CC) and a constant voltage (CV) portion. It was also noticed that the energy consumed during charging is more than the actual energy supplied to the battery. This additional energy is probably used to support the vehicle battery cooling systems and other supporting electronics such as the battery management system.

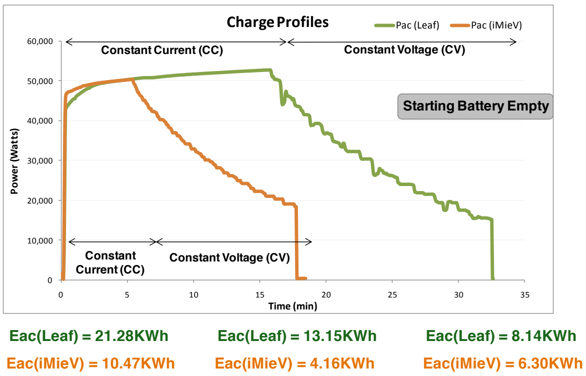

Figure 5: Full Charge Cycle Comparison between Nissan Leaf and Mitsubishi iMieV

When charging from partially full batteries (50% state of charge and higher), it was noticed (shown in Figure 6) that the charging rate decreases or in other words, the amount of time taken to charge increased. Example-when starting from a remaining battery capacity of 17.2 kWh, it took 34 minutes to add just 3.5 kWh of energy. This is however still less than the time consumed by a Level 2 240 V AC charging (shown in Figure 7) when started from a similar remaining battery capacity. Further, as charging is started with higher and higher remaining battery capacities, the CC mode portion of the charging decreases. When started with 17.2 kWh remaining, all charging takes only in CV mode.

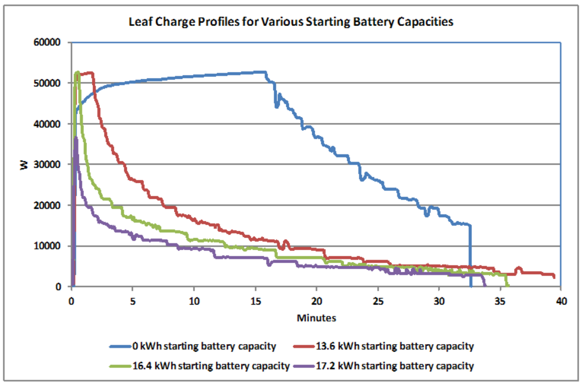

Figure 6: Nissan Leaf Charge Profiles for Various Starting Battery Capacities

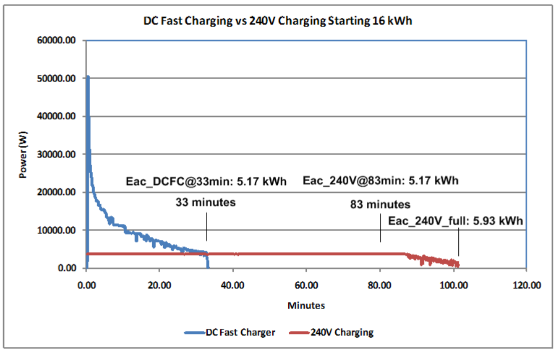

Figure 7: Level 2 DC Fast Charging and Level 2 240V AC Charge Profiles for Starting Battery Capacity of 16 kWh (Nissan Leaf)

Peak efficiency of the commercial fast charger occurs at around half rated power and is around 90.5% for 208V/230V system and about 92% for 480V/400V systems. This is illustrated in Figure 8. For 208V systems, efficiency during maximum power (that typically occurs when the DC fast charger is in the CC mode) is around 89.6%.

Harmonic/spectral analysis on both the input and output voltage/current were conducted. Input harmonic analysis revealed that while the overall THDs are low, a non-negligible third-harmonic component is present. This third-harmonic probably arises from a single-phase supply or fan, and could present issues when connected to the utility grid that has significant single-phase loads.

The key takeaways from the detailed testing 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.

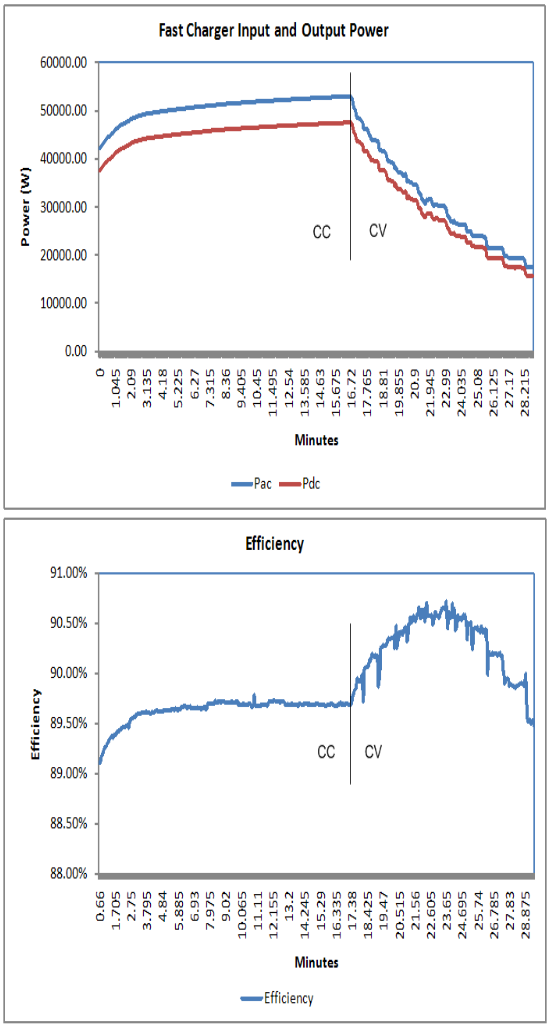

Figure 8: Nissan Leaf Input and Output Power Charge Profile and Associated DC Fast Charger Efficiency

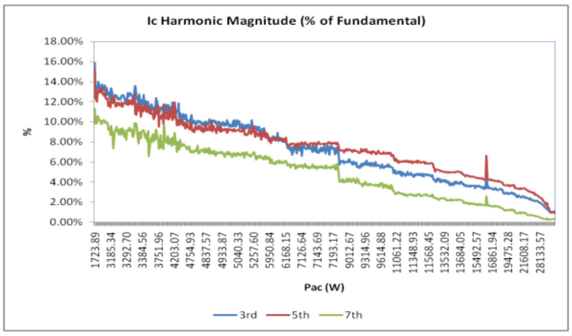

Figure 9: Variation of 3rd, 5th, and 7th harmonic Observed on one of the Phases (Ic)

5 EPRI's Utility Direct Medium-Voltage DC Fast Charger

The Utility Direct Fast Charger (UDFC) technology shown in Figure 10 enables the rapid charging of an electric vehicle (EV) and can also serve as a utility-owned distribution asset that can be used for other electricity delivery purposes. The UDFC is a direct medium-voltage to charger concept and is based on EPRI's Intelligent Universal Transformer (IUT).

EPRI has been developing solid-state transformer technology known as Intelligent Universal Transformer (IUT) for a number of years and has developed important fundamental designs (see Figure 10) to enable the next steps of actual demonstration that can lead to commercialization of the technology. These designs have been demonstrated through prototype and controlled laboratory testing. The market for the technology, however, has changed over the last few years with growing penetration of photovoltaic generation; need to provide DC power for data centers, and the expected penetration of electric vehicles that may have a need for fast charging.

Over the last two years, EPRI has developed two medium voltage[1] IUT prototype systems for 4KV and 15KV class distribution system applications that applies solid-state technology for voltage conversion and provides additional functionality expected to offer distict advantages in a more complex delivery system, benefitting consumers and utilities.

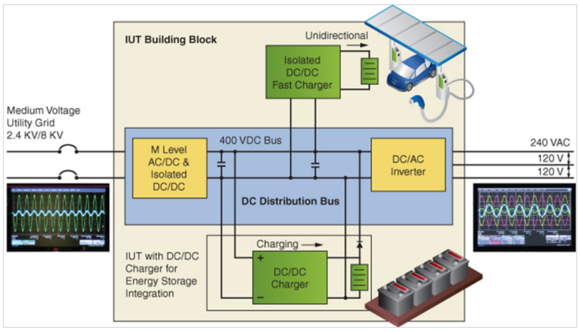

Figure 10: IUT Modular Reconfigurable Solid State Medium Voltage Transformer System – An Important Option for Local Voltage Control, Distributed Resource Integration, and Electric Vehicle Charging

The IUT converts alternating current (ac) power at various distribution level voltages to direct current (dc) and ac power ready for residential and commercial use. The IUT technology replaces both the independent power conversion units as well as the conventional transformer with a single interface system which can be used for fast charging of electric vehicles. The versatility of the IUT provides an intermediate DC bus voltage at the 400-V level that can be directly used for a DC distribution system or for EV fast charging.

The Utility Direct Fast Charger technology uses fewer components than comparable DC fast charging technologies being designed and used today. Its simple design is expected to result in lower installation costs and to be significantly more efficient than currently available commercial DC fast charging systems.

Conventional DC fast charging systems can attain efficiencies in the 90-92% range. When this is combined with the efficiency of a required three-phase supply transformer, the overall efficiency drops to 89-91%. The EPRI Utility Direct Fast Charger technology is expected to achieve an overall system efficiency of 96-97%.

5.1 Summary of the IUT Development, Testing, and Demonstration

EPRI is leading the development and demonstration of a fully integrated, production-

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[1] It should be noted that, in the utility world, the term "medium voltage" refers to a range of kilovolt-level ac voltages (4 kV to 35 kV) used for power distribution across the grid. Within this medium voltage range there are also voltage classes. Systems with voltage levels up to 4 kV are designated as 4-V class distribution systems, while systems with levels up to 15 kV are designated as 15-kV class distribution systems. Both types of systems are found in the utility grid.

grade 4-kV and 15-kV-class solid-state transformer for integrating energy storage technologies and EV fast charging. The development team includes utilities, power electronics experts, and a transformer manufacturer to provide guidance on taking the technologies from concept to production. The IUT technology has been validated through development and lab testing and includes the following milestones:

- 2.4kV, 25kW IUT successfully tested at EPRI-Knoxville (July 2011)
- 2.4kV, 50kW EV Fast Charger successfully tested at EPRI-Knoxville (March 2012)
- 2.4KV 50kW EV Fast Charger successfully demonstrated at Plugin conference in San Antonio (July 2012) – Figure 11
- 2.4KV Variable Power (50, 45, 35, 25KW) EV Fast Charging successfully tested at EPRI-Knoxville (January 2013)
- 7.2kV, 25kW IUT successfully tested at Howard Industries (May 2013) – Figure 12 – Figure 14

The charging events in Knoxville and at Plug-In 2012 in San Antonio using a Nissan Leaf and a Mitsubishi iMiEV as the test targets consistently showed higher than 96% efficiency measured from 2.4-kV input to the vehicle output. An 8-kV UDFC is presently under development with the medium-voltage front-end already validated through internal tests. This unit is expected to exceed 97% system level efficiency. Efforts to commercialize this technology are now underway with select vendors.

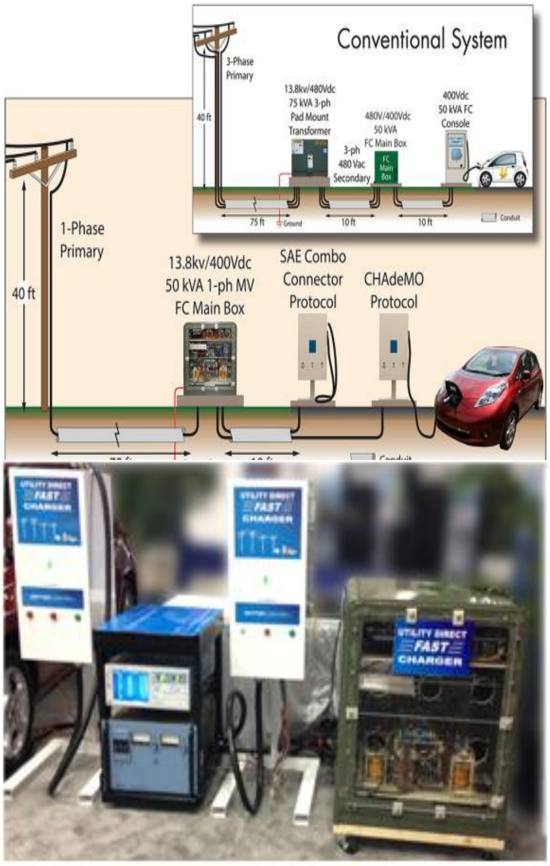

Figure 11: Utility Direct Fast Charger (UDFC)

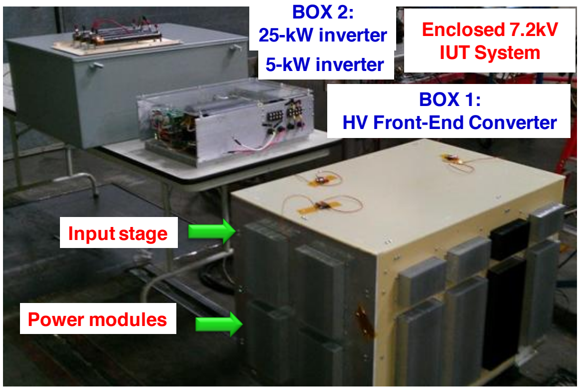

Figure 12: 7.2KV 25KVA IUT System

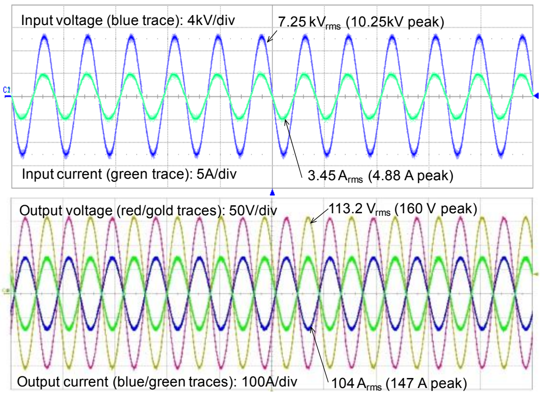

Figure 13: IUT Input and Output Voltage and Current Waveforms under 7.25kV, 25kW Condition

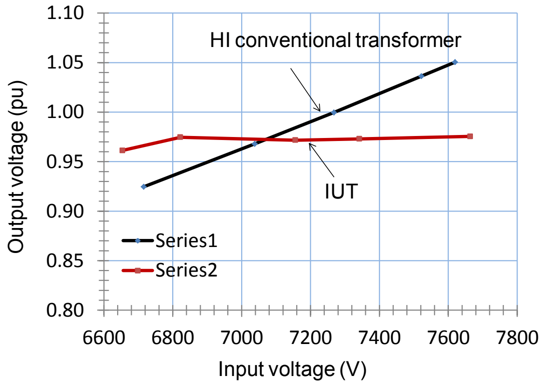

Figure 14: Voltage Regulation Comparison Between Conventional Transformer and IUT

5.2 Variable Power Fasting Charging using UDFC

As demand charge is considered to be one of the potential barriers to installation of DC fast chargers, fast charging with lower power levels has been widely debated. Using an EPRI-developed DC fast charging system, charge profiles at various charging powers were captured. This is illustrated in Figure 16.

There are quite a few interesting observations that can be drawn here. The charge durations progress on-linearly with power. The durations for 60A and 80A are similar as are the 100A and 120A. Further, it appears that the transition from constant current to constant voltage appears to be happening at around 60% SOC as shown in Figure 17 and Figure 18.

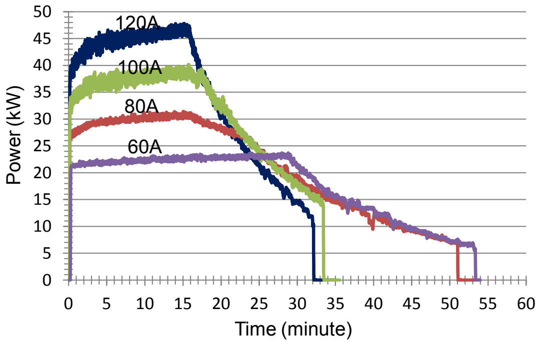

Figure 15: Charging Power Profiles under Different Command Current using UDFC

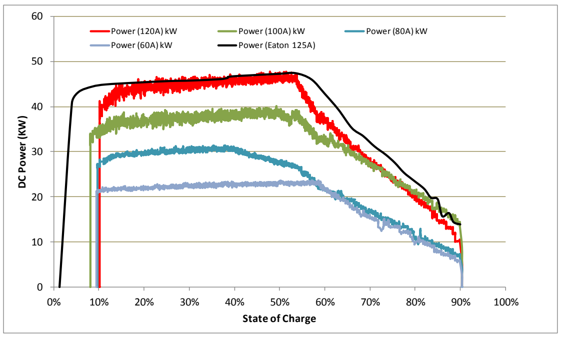

Figure 16: Power versus SOC Variations using UDFC

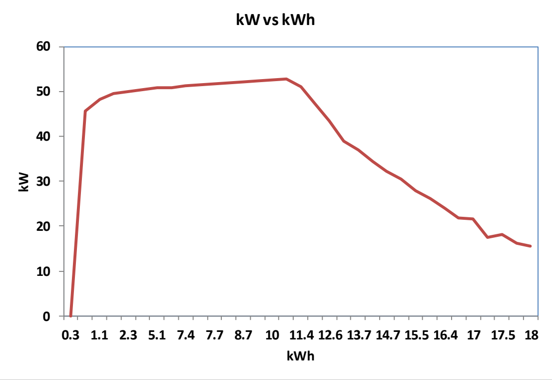

Figure 17: Power versus Energy Variations using UDFC

6 Application of Results

The results described here are meant to provide a better understanding of the capabilities, market status, and potential impact of fast charging on both the consumer as well as the electric grid. Advanced technologies such as the UDFC offer the promise to make DC fast charging economically viable furthering widespread adoption. After utility-ready, production-grade units undergo validation and acceptance testing, they will be deployed for field demonstration within the service territories of several utilities.

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