Exclusive Technology Feature

ISSUE: April 2012

Utility Direct Technology Boosts Efficiency Of Fast Charging For Electric Vehicles

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A team of engineers and scientists from the Electric Power Research Institute (EPRI) and Enertronics, with financial and technical support from the Tennessee Valley Authority (TVA), has developed a new type of fast battery charging technology for electric vehicles (EVs). The medium-voltage fast charger technology is based on a solid-state transformer that will allow electric vehicle charging to interface directly with a utility's electric distribution delivery system. The Utility Direct Fast Charger technology uses fewer components than comparable dc fast charging technologies being designed and used today, is expected to offer lower installation costs, and is significantly more efficient than currently available commercial dc fast charging systems (Fig. 1.)

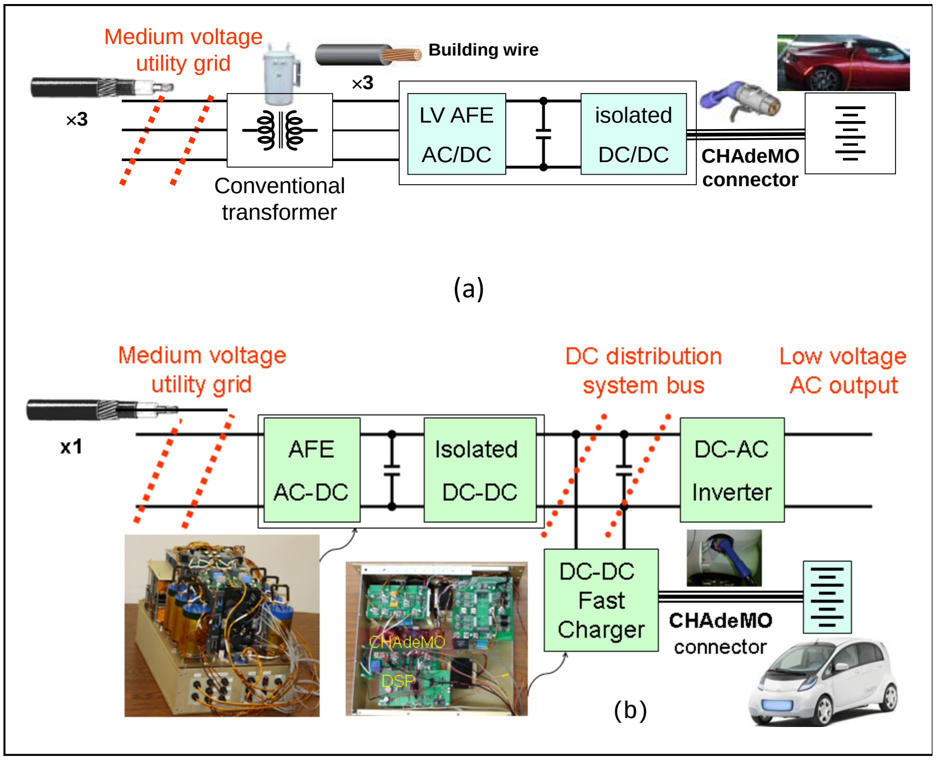


Fig. 1. A conventional dc fast charging system for electric vehicles (a) is compared with EPRI's Utility Direct Fast Charger (b). The conventional fast charger typically operates from 480 or 208 V ac, while EPRI's charging system operates from the 2.4 kV "medium voltage" that is normally fed to the utility's three-phase power distribution transformer (labeled "conventional transformer" in part a of the figure.)

The efficiency benefit of this new fast charging technology is particularly compelling. Consider that conventional dc fast charging systems can attain efficiencies in the 90% to 92% range. When this charge efficiency is multiplied by that of the required three-phase power distribution transformer, the overall efficiency of the conventional charging system drops into the 89% to 91% range. In contrast, the EPRI Utility Direct Fast Charger technology is expected to achieve an overall system efficiency of 96% to 97%. Moreover, the new technology will enable the rapid charging of plug-in electric vehicles (PEVs), while also creating a utility-owned distribution asset that can be used for other electricity-delivery purposes.

At its Knoxville, Tennessee laboratory, EPRI recently demonstrated the first prototype of the Utility Direct Fast Charger technology in the form of a 2.4-kV 45-kVA solid-state, dc fast charging system for electric vehicles (Fig. 2.) This article presents test results for this prototype and compares those results with those of conventional dc fast charging systems, which operate from lower input voltages. Benefits of the new charging technology and the underlying solid-state transformer concept and their applications are discussed.

Demonstration Results

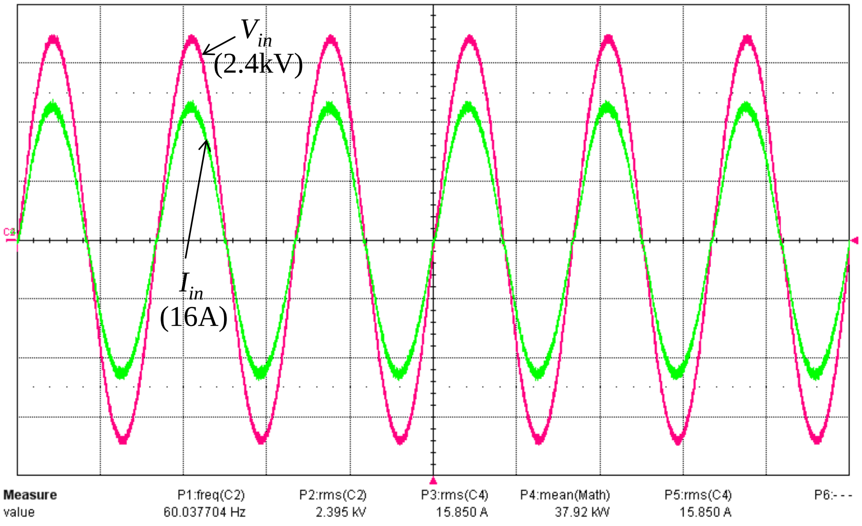
Recent testing by EPRI has confirmed the 2.4-kV 45-kVA fast charger prototype's ability to provide a full vehicle charge to commercially available plug-in electric vehicles. Two Nissan Leaf and one Mitsubishi iMiEV electric vehicles were successfully charged using the EPRI Utility Direct Fast Charger. An important part of the demonstration was to verify the communications compatibility of the fast charging technology with the electric vehicles' battery management systems using the industry-standard CHAdeMO communications protocol. A user interface and web-based mobile data collection system were included in the Knoxville trials.

Fig. 2. As proof of concept for EPRI's Utility Direct Fast Charger technology, EPRI's developed and demonstrated this prototype of a 2.4-kV 45-kVA solid-state, dc fast charging system for electric vehicles.

Fig. 3 shows the input voltage and current waveforms at 2.4-kV ac input and 38-kW output. The current THD is less than 2%, and the power factor is unity. With an entry-level medium voltage of 2.4 kV, the input-side current is only 16 A. For three-phase inputs of 480 V and 208 V, this current could have been more than 50 A and 110 A, respectively.

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.

This first EPRI Utility Direct Fast Charger prototype represents equipment that would be compatible with a 4-kV class distribution system. EPRI's next step will be to build a fast charger prototype with 8-kV input, which would represent compatibility with a 15-kV class distribution system. Therefore, this second prototype will demonstrate the viability of EPRI's Utility Direct Fast Charger design for 15-kV class systems that use a medium voltage level such as 12.47 kV, 13.8 kV, etc.



Measure	P1:freq(C2)	P2:rms(C2)	P3:rms(C4)	P4:mean(Math)	P5:rms(C4)	P6:- - -
value	60.037704 Hz	2.395 kV	15.850 A	37.92 kW	15.850 A	

Fig. 3. Input voltage and current of the Utility Direct Fast Charger prototype measured at 2.4-kV input and 38-kW output conditions.

Fig. 4 compares Leaf and iMiEV charging profiles with an 80-A current setting. The actual charging current is controlled by the EV's battery management system (BMS), which ensures that the EV's Li-ion batteries receive the appropriate charging current in accordance with their required constant-current then constant-voltage charging profile. The BMS in the Leaf commands a current with linear reduction rate to maintain a slow linear voltage increasing rate when the battery voltage exceeds 384 V. The iMiEV's BMS, however, maintains the constant-current charging for a longer period until the voltage reaches 364 V. After that, it maintains constant-voltage charging with a nonlinear current reduction rate. The shutdown command in both cases was pre-programmed at 80% state of charge (SOC).

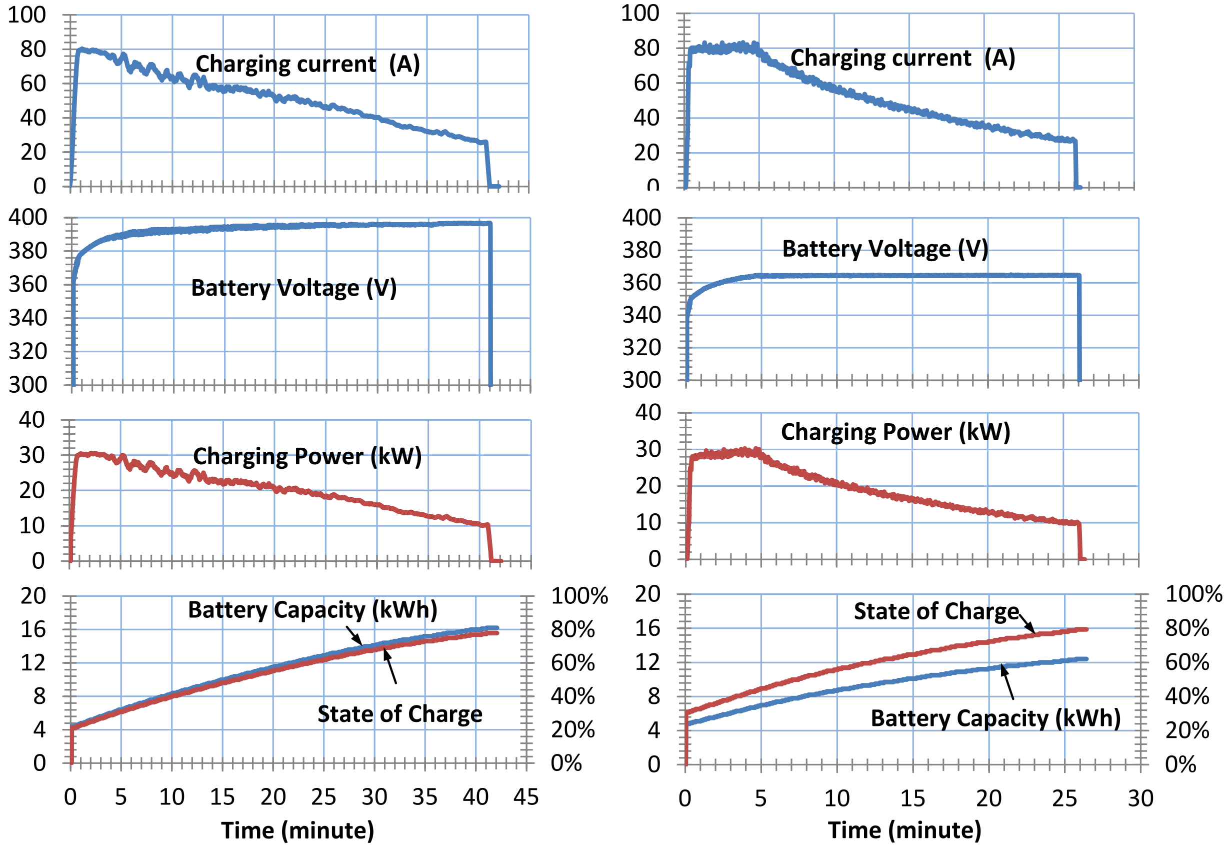


Fig. 4. Leaf charging profile (a) and iMiEV charging profile (b), both at 80-A charging current.

In addition, the demonstration compared the new technology's performance with that of a commercial 3-phase dc fast charger (Fig. 5.)

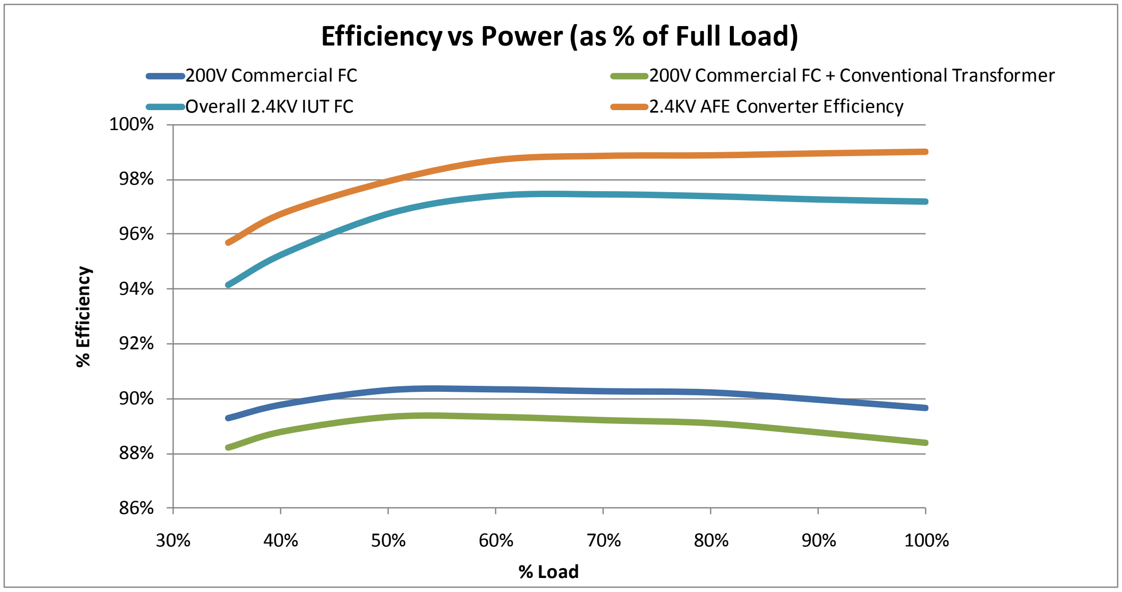


Fig. 5. Efficiency of a 2.4-kV 50-kW medium-voltage Utility Direct Fast Charger compared with that of a commercially available dc fast charger.

A Closer Look At The Technology

The Utility Direct Fast Charger implements the CHAdeMO protocol that is presently deployed on several production electric vehicles including the Nissan Leaf and the Mitsubishi iMieEV. In addition to electric vehicle charging, the system can also serve as an intelligent smart grid communications node, integrate photovoltaic (PV) energy generation and storage, and simultaneously perform the role of a utility-owned distribution transformer supplying multiple residential loads.

The system offers dramatic efficiency improvements over its conventional counterparts. Commercially available dc fast charging systems for electric vehicles are three-phase systems that require significant capital investment for installation, have low efficiencies that are typically <92%. By comparison, the EPRI developed technology is rated at >96% efficiency.

If you compare by total cost of ownership, conventional technologies fall somewhere between $30,000 and $45,000 per charging station, plus additional dollars equal to or greater in installation costs. The EPRI-developed technology is expected to fall between $31,000 and $40,000 for total cost of ownership per station. It will also result in less than half the installation costs of conventional technology. There are currently no utility-owned systems that integrate the functionality of UPS systems, electric vehicle fast charge management and control of local loads. EPRI's new EV charging system includes this functionality.

Where This Technology Makes Sense

There are two scenarios where this Utility Direct Fast Charge technology could be applied:

1) Utilities who want to provide fast-charging capability directly from their distribution system. This could be especially useful in dense cities where you place fast chargers that aren't hosted by a business.

2) Businesses could install solid-state transformer technology, described below, as their building transformer and conveniently add fast charging service (and also integrate their onsite solar, energy storage, and building energy management system.) This would help in managing the high peak loads of the dc charger and the impact both on the utility and to a business' own cost of service, specifically by reducing demand charges.

Dc fast charging technology has the potential to significantly increase the range and versatility of battery electric vehicles, enhancing their commercial appeal. Prior research by EPRI indicates that current electric vehicles have sufficient range for most daily driving. So eliminating concerns about vehicles requiring extended charging periods will enhance the appeal of EVs to consumers.

Solid-State Transformer Technology

Distribution transformers in use today were conceived, developed, and refined over a century ago to do one function—step down the electricity supply voltage to a level that can be used safely by customers. But advances in higher-voltage power electronics could completely change that and introduce a flexible, intelligent device in its place that is not limited to voltage conversion—the solid-state distribution transformer.

The concept of the solid-state transformer is not new but the convergence of a number of trends suggests this equipment will be moving from R&D to commercialization within the next three to five years.

- The availability and volume-based cost reduction of capable semiconductor components.
- The proliferation of distributed renewable generation, which is expected to introduce grid stability concerns as they exceed 20% to 25% circuit penetration levels.
- The solid-state transformer fits logically with the envisioned smart grid, which has embedded intelligence, network connectivity and remote manageability.
- Growth of EVs and their associated load profiles will require flexible distribution assets that can manage differing load profiles in real time.

The solid-state transformer is a multifunctional device that consists of transistors, diodes, and other semiconductor-based components engineered to handle high power levels and very fast switching rates. The solid-state transformer designs currently in development also have processors and communications built-in, enabling them to respond to a utility or customer signal and change voltage as well as other characteristics of power.

A combination of universities, established market leaders, and early stage start-up ventures are in varying stages of solid-state transformer (referred to as "SST") development at present. Leading these efforts are the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center and the Electric Power Research Institute.

Two companies, ABB and Cree, are members of FREEDM Center and are working closely with the research team to commercialize the solid-state transformer design.

EPRI named its solid-state transformer the Intelligent Universal Transformer (IUT) and began developing the concept as early as 2004. After a thorough evaluation of industry needs and material advancement, EPRI is now leading the development and demonstration of a fully integrated, production-grade 4-kV and 15-kV-class solid-state transformers for integrating energy-storage technologies and EV fast charging.

EPRI successfully demonstrated a lab-scale IUT in December 2010 and a field-prototype 2.4-kV, 25-kVA model with enclosure, packaging, and high- and low-voltage bushings was deployed for evaluation in 2011 at Northwest Utilities (Fig. 6.)


2.4kV IUT Prototype (2010 lab test)

Fig. 6. Images of the IUT prototype.

A fully functional EV fast charger system at 2.4-kV input and 45-kW output was designed, along with a variety of communications and performance features, and was demonstrated at the EPRI Knoxville Tennessee laboratory on March 2012.

A Closer Look At EPRI Solid-State Transformer Technology

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 line-to-line) to the required lower ac voltage. Altogether, 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 electronics stage (the first stage within the dc fast charger that converts 480 V ac into an intermediate dc voltage)
- Dc-dc power electronics 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) (see Fig. 7.)

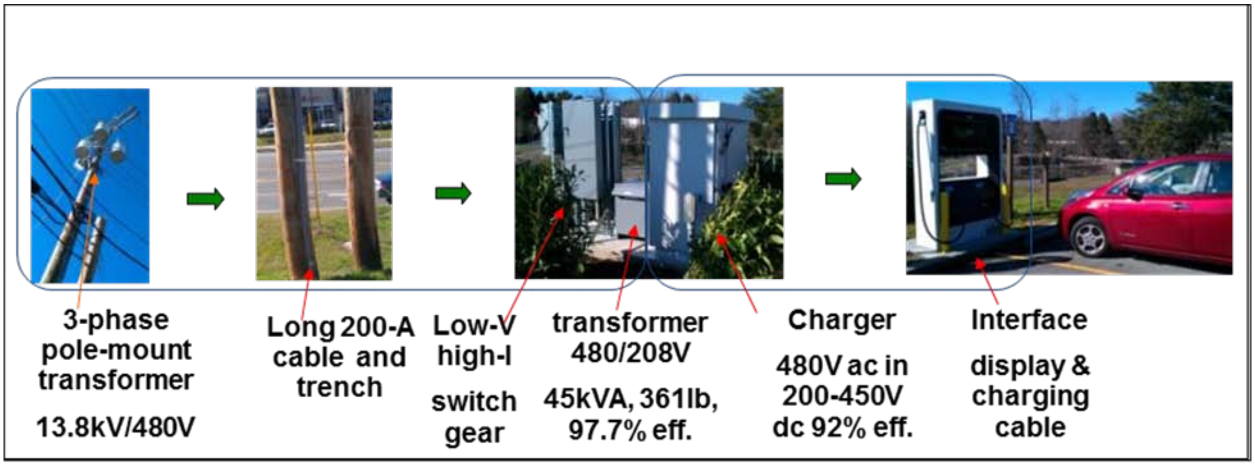


Fig. 7. Infrastructure (components and cabling) associated with commercially available dc fast chargers.

At low voltages, the input current is typically large, 90 A at 480 V ac or 200 A at 208 V ac, resulting in increased losses and lower efficiency. Most dc fast chargers have efficiency in the 90% to 92% range. When combined with the efficiency of the three-phase transformer (~99%), the overall system efficiency (excluding losses on the low-voltage runs) is between 89% and 91%. If the secondary drops (runs) are included, the overall efficiency can be expected to decrease further.

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 (Fig. 8.) 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. By leveraging the IUT technology, the Utility Direct Fast Charger has the potential to achieve efficiency higher than 96% in the 10%-to-90% loading range, a savings of >6% over the conventional approach.

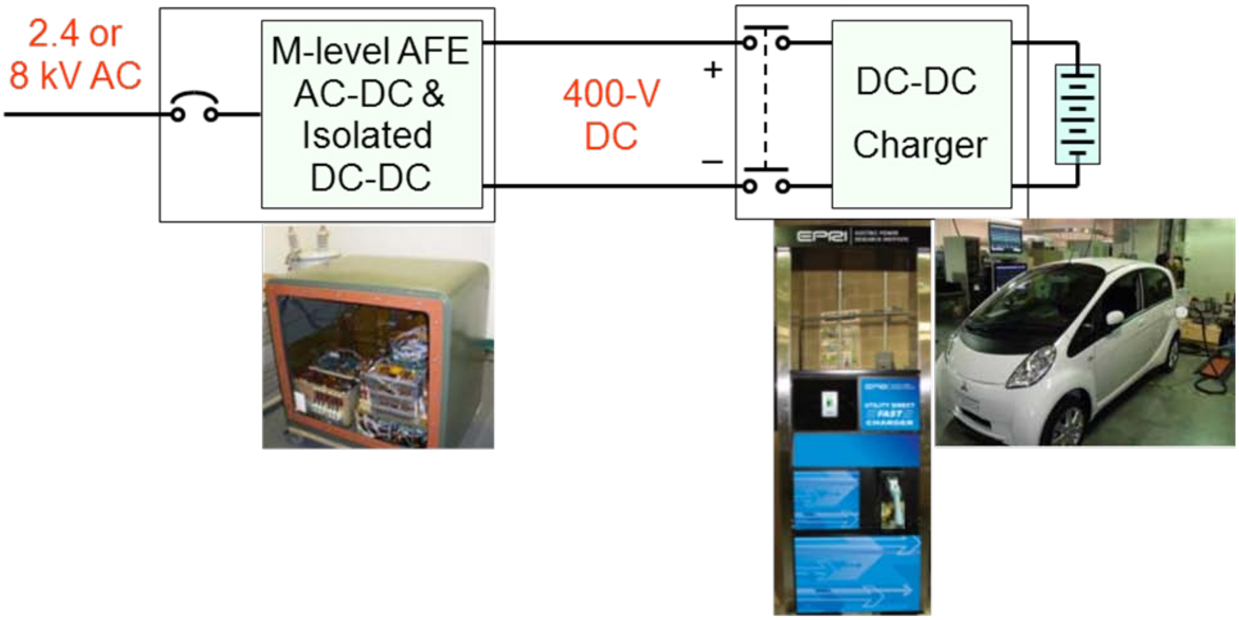


Fig. 8. Components of EPRI's Utilty Direct Fast Charger. EPRI's first charger prototype is a 4-kV class unit that operates from a 2.4-kV input. EPRI plans to build a second charger prototype for the 15-kV class that will accept an 8-kV input.

For a dedicated dc fast charger where the dc-ac inverter is not needed, the isolated dc-dc converter output can be directly used for fast charging, avoiding an additional 1.5% energy loss. The elimination of the conventional transformer also allows significant size and weight reduction on cabling and installation. The standard ANSI based 50-kW transformer weighs more than 800 lbs. The entire charging station including the low-voltage-based charger will weigh more than 1000 lbs. On the other hand, the weight of the entire EPRI Utility Direct Fast Charger electronics is less than 150 lbs.

About The Author

Arindam Maitra is a senior project manager at the Electric Power Research Institute (EPRI). He is responsible for leading and managing activities related to the power system infrastructure requirements for plug-in hybrid vehicles. He is also conducting and managing numerous research activities associated with power systems and power electronics.

Prior to joining the Electric Transportation group, Maitra worked as a senior project manager in the System Analysis and System Studies group (previously EPRI Solutions and EPRI PEAC). In this role, he conducted and managed a wide range of research activities and power system studies in the transmission, distribution, power quality, and IntelliGrid research areas. He also managed projects related to reliability improvement, power electronic development efforts, indices for describing power quality and reliability performance, and load model development. Maitra holds two patents for the Intelligent Universal Transformer design topology and one patent in solid-state switchgear topology.

Maitra received his Bachelor of Engineering degree from the Regional Engineering College, Nagpur, India, and holds a Master of Science and a doctorate in electrical engineering from Mississippi State University. He is an active member in IEEE and IAS working groups. Maitra is also a recipient of the 2005 and 2010 Chauncey Award.