*EVS25*
*Shenzhen, China, Nov 5-9, 2010*

# Synchrophasors, Active Transformers, and Energy Storage in the Context of Fast Charge EV Infrastructure

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## Abstract:

Electric vehicle (EV) fast charging capabilities, and availability of fast charge infrastructure, are perhaps the greatest remaining obstacles in the future widespread use of EVs. Solving fast charging paradigms and issues will enhance driver and electric utility acceptance of EVs. Potential impact to the grid is one of the perceived issues. The technologies to transform EV fast chargers, a grid load, into a valuable grid asset, exist in the form of components and a system approach that includes:

- Synchrophasors
- Active Transformers
- Grid-Level Energy Storage
- Demand Response and Time of Use pricing

Many of these technologies and strategies are in place or in the advanced stages of development. This would allow this system approach to become commercial as the widespread adoption of EVs unfolds.

**Keywords:** EV Fast Charging, Synchrophasor, EV Charging Infrastructure

## 1 Introduction

AeroVironment, Inc. developed the Impact prototype electric vehicle (EV) for General Motors in 1989. GM then converted the Impact from prototype to the first production-class electric vehicle, EV-1, and marketed it in 1996 and 1999.

**Figure 1. EV Development Timeline**

From the early days of the Impact/EV-1 program, AeroVironment focused development on the charging paradigm. Issues included user safety, vehicle safety, battery chemistry, battery management systems, battery pack development, pack testing and validation, charger power electronics, vehicle/charger interface, inductive vs. conductive charging schemes, and direct current (DC) power delivery methods and connectors. In the 1990's, utilities and other stakeholders focused only minimally on charging infrastructure grid impacts. This focus has changed greatly in the intervening decade.

Today, electric utilities worry whether neighborhood transformers, whose normal duty cycle allows them cool down overnight, will hold up to overnight EV charging. They also worry that power spikes from EV fast charging could negatively impact grid stability and capacity, especially during peak grid usage. This paper focuses on the degree of fast charging grid impacts, grid compensation techniques in the form of grid-level energy storage acting as distributed generation; emerging communication and control technology with the advent of the Smart Grid movement; and active transformers in the context of a system approach. Also discussed is the cost effectiveness of these compensation techniques.

## 2 Charge Scheme Definitions

### Synchrophasors and Smart Grid Communication and Control

Synchrophasors are precise measurements of the phase angles of voltage, current and frequency at dispersed locations on the electricity grid. Synchrophasor measurements are taken from grid monitoring devices called phasor measurement units (PMUs) at high speeds of thirty observations per second. This is more than two orders of magnitude faster than Supervisory Control and Data Acquisition (SCADA) techniques, which measure once every four seconds. Because synchrophasors are measured at discrete points in time and space (via Global Positioning System – GPS), they can be correlated and synchronized against grid activity. This also enables grid operators to combine synchrophasors to provide an instantaneous, all encompassing view of the grid, which includes systemic changes and grid stresses. Most importantly, synchrophasors provide grid operators a much needed tool to potentially control these stresses with the advent of smart grid technologies coming into play over the next few years. [1]

Synchrophasors, via PMUs, may act as a potential component in the system approach to EV fast charger compensation and grid asset management.

### Active Transformers

Conventional transformers that tie into medium voltage grid feeder lines have high efficiencies, but create potential power factor issues. Active transformers, or power converters, for medium voltage (13kV) use fast switching transistors and high frequency transformers that can provide a unity power factor. Applications for this type of power converter include:

- Unidirectional power flow from the grid to 240/480V 3-phase commercial/industrial equipment
- Bi-directional power flow between the grid and electric vehicle charging equipment
- Bi-directional power flow between the grid and energy storage devices

Operationally, the active transformer accepts power from a 13kV (or similar) grid feeder line and provides power to the commercial/industrial equipment, EV direct current (DC) charger, or grid energy storage device and allow for bi-directional flow. This is especially important for energy storage devices providing grid ancillary services such as frequency regulation and for EVs providing vehicle to grid (V2G) services. If desired, leading power factor can be provided to achieve "VAR Compensation". The advantage of this is that losses within the grid distribution system can be reduced.

### Grid-Level Energy Storage

This paper restricts the discussion of grid-level energy storage to batteries. Grid-level battery systems for grid frequency regulation, for example, typically are a megawatt of power (MW) and one-half megawatt-hr (0.5MW-hr) of energy storage and greater. Battery systems typically require a bi-directional inverter and transformer as the traditional method for grid connection. An active transformer could combine these functions into a more robust and efficient grid interface.

**Fast Chargers and Communication with the Grid**
Fast charger products, as defined for this paper, range from 30kW to 250kW, provide DC power at medium voltage (250V and above), and allow EV charging in ten to thirty minutes depending on the battery state of charge, battery type, and other factors. Fast chargers have communication modules that provide not only grid communication, but operational data to the charger operator and other stakeholders via an Internet back office service.

Figure 2: DC Fast Charger

EV chargers, both on-board and off-board the vehicle, are electronic-based charging systems that convert AC utility power into controlled DC power to charge the EV battery pack. The EV charger design must meet all regulations for automotive, electric outdoor equipment, while providing a simple interface for ease-of-use and acceptance by EV drivers. The charger typically comprises an external utility isolation transformer and the charging module. The charging module is capable of operating from 3-phase utility input voltage ranging from 400-600VAC (50or 60Hz) and delivering up to 600Amps DC to charge battery packs up to 500VDC for passenger vehicles and higher voltages for heavy duty vehicles such as buses. A 250kW charger, for example, is capable of charging a 35kWh battery pack (0-100% SOC) in less than ten minutes. To meet future Vehicle-to-Grid (V2G) infrastructure requirements, EV chargers will need to provide bi-directional power flow.

The initial introduction of EV fast chargers in Japan and the US include 50kW products, based on the CHAdeMO™ standard. A coalition of Japanese automakers and engineering leaders including Toyota, Mitsubishi, Nissan, and Fuji Heavy Industries teamed up with the Tokyo Electric Power Company (TEPCO) to form the CHAdeMO (Charge de Move) Association, a group interested in standardizing EV charging stations to work for all vehicles. The 50kW CHAdeMO EV chargers allow a Nissan LEAF™ or Mitsubishi iMiEV™ to be charged within approximately thirty minutes.

# 3 Local and System-Wide Grid Issues

Electric utilities representatives have voiced the concern that fast charging could negatively impact the grid. Their argument is that placing multiple (8 to 10) 250kW loads, or fast chargers, on a remote distribution feeder line could induce voltage sag and enhance congestion. Many discussions of the EV fast charger business case, however, focus on installations of one to two fast chargers in any given location. And while 250kW EV chargers will no doubt make their way to the market in the long term, the 50kW CHAdeMO chargers have made a strong market statement.

**Local Line Impacts.** For the sake of argument, however, we examine the case where a conventional gasoline station has been converted to a bank of eight 250kW fast chargers as shown in Figure 3. Extensive modeling for this case examined four actual feeder line locations in the territory of a Nevada, USA utility, called NV Energy, that ranged from 13.2kV to 24.9kV (Reno, Nevada) [2]. The study made worst case assumptions with all eight vehicles simultaneously charging at the same time.

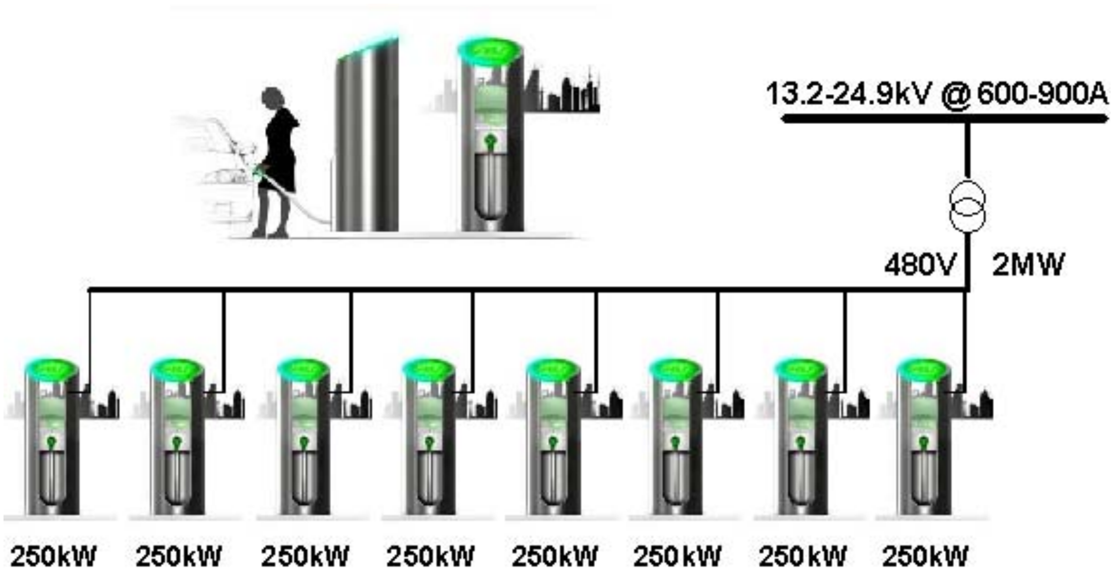

**Figure 3. Eight 250kW EV fast chargers on a 13 or 25kV low voltage neighborhood line**

In two of the locations (24.9kV lines), simulations demonstrated that eight EVs could be charged simultaneously with minimal voltage sag impact. The other 24.9kV line location showed voltage sag with more than three EVs charging simultaneously, while the 13.2kV line location showed only one EV could be charged without grid impact. Simulations were performed, however, assuming no assistance from compensation techniques such as ramp up, an onsite energy storage facility, or interlock strategies. The study concluded that the effect of a proposed EV fast charging station will be dependent on the utility system site and that compensation techniques may be necessary.

Based on the study, even the 13.2kV distribution line, without the use of compensation techniques, would easily handle multiple CHAdeMO 50kW EV fast chargers at a single location, while simultaneously charging vehicles at full power.

**Fast Charger Controls.** EV fast chargers typically ramp up power levels rather than supply instantaneous power. This alleviates short time scale grid shocks. They are also designed with the capability to continuously communicate with the grid. If a problem occurs with the distribution line the utility could command the EV charger(s) to ramp down in power level, or shut down completely as a form of Demand Response.

**Battery Energy Storage.** For weak grid distribution lines, charging schemes that include battery storage between the grid and the charger bank, as detailed in a recently issued patent [3], could provide a buffer and further reduce the potential for adverse grid impacts. Indeed, utility control, coupled with a high peak use rate structure, is designed to modify consumer behavior and could minimize potential grid impacts from fast charging.

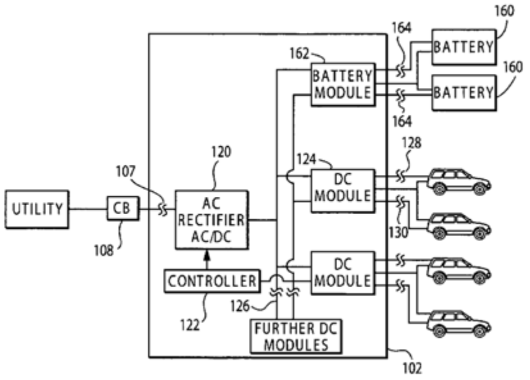

**Figure 4. Illustration from a Utility Bi-Directional EV Charger Patent**

For grid services, including compensation for distribution lines, the energy storage technology should have a high round trip efficiency, a high power to energy ratio, and a system life of at least ten years. Flow batteries are often mentioned and are in use for many demonstration projects, but have relatively low round trip energy conversion efficiency and a low power-to-energy ratio. They may be better suited to peak shifting applications. Lithium batteries, of which several chemistries are on the market, are also the subject of many demonstration projects. They exhibit extremely high round trip efficiency. Two specific lithium chemistries, iron phosphate and lithium titanate (titanium oxide), have high power-to-energy ratios, high cycle life and long calendar life. Lithium titanate, if proven cost-effective, appears ideally suited to distribution line compensation [4].

**Active Transformers as Compensation.** As mentioned in the definition section, active transformers have the capability to reduce distribution line losses. They can play an important role in the system approach to compensation and grid stability for weak distribution lines. Active transformers are currently in the development and prototype stages awaiting further development and commercialization of silicon carbide-based fast switching transistors, control algorithms, and packaging.

**Synchrophasors and Grid Health.** Synchrophasor measurements are most often considered in the context of wide-area grid monitoring and visualization. Many other applications, such as automated real-time control of assets, power system restoration, and dynamic and static model validation are also in use.

Electric utilities monitor grid activities with supervisory control and data acquisition (SCADA) techniques, which provide data not normally useful in fast responses for controlling grid problems because the sample rates are low and the measurements are not synchronized. SCADA techniques are used to monitor local areas. As phasor measurement units (PMUs) become more widespread and costs decrease for implementation, the use of synchrophasors for such applications as congestion analysis, operations planning and state estimation will become common [5]. This will allow grid operators to bring on line a crucial aspect of the Smart Grid at the grid system level. From the end-user side of the Smart Grid come smart meters, smart consumer devices and smart EV chargers.

**Synchrophasors and Local System Applications.** While SCADA techniques are used for local monitoring, synchrophasor measurements allow grid operators to apply static VAR compensation, protective relay control and other system asset control. This also allows identification of assets that can respond in real-time to local grid problems. For existing grid assets with phasor measurement technology, synchrophasor functionality may be added to provide increased control. Conceivably, adding synchrophasor functionality via GPS, time synchronicity (standard IRIG-B format time code), and voltage and current inputs/filtering to an EV fast charger/transformer system (especially multiple chargers) has the potential to turn a traditional grid load into a valuable compensation asset.

With the ability of the future Smart Grid to monitor assets and grid health via synchrophasors, if a feeder line were to exhibit congestion, voltage sag or other issue, a grid controller could automatically signal a fast charger to reduce charge power level or cease operation altogether as depicted in Figure 5.

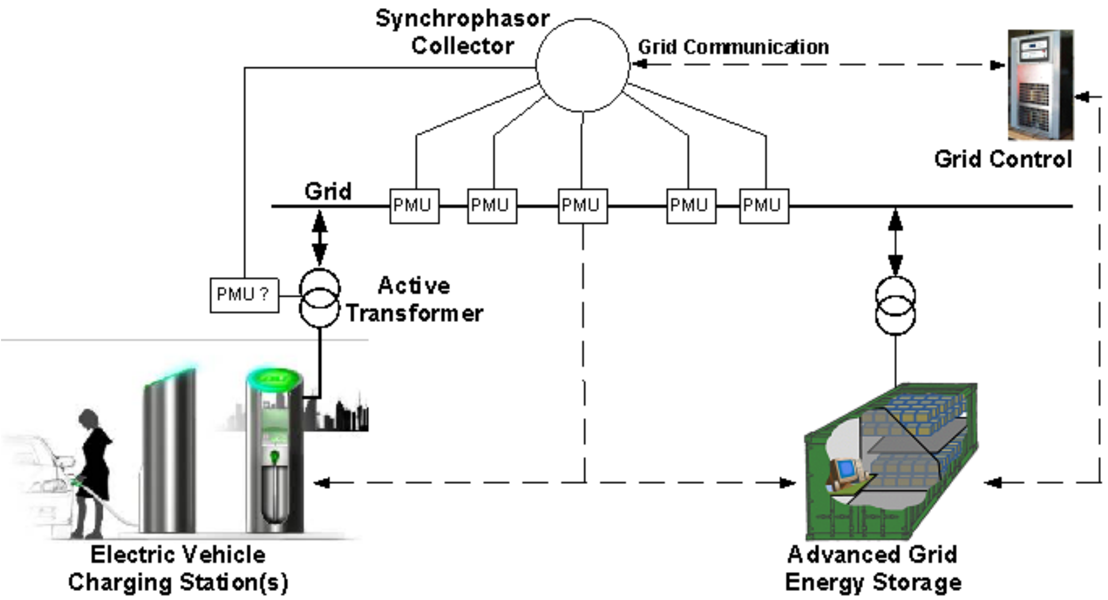

**Figure 5. Smart Grid use of synchrophasor and advanced energy storage for fast charging**

**Electric Utility Time-of-Use and Demand Response.** Time-of-Use pricing (TOU) allows electric utilities to price electricity according to the time of day and value of grid electricity at the time. Electric utilities have, and are in the process of applying the TOU pricing technique to modify the behavior of residential, commercial and industrial customers. This technique could also apply to EV drivers, where the electric utility could price a fast charge event at several times the $/kWh rate during a late summer afternoon peak use period versus six in the morning.

Electric utilities use Demand Response as a more active technique than TOU to actually curtail loads, when necessary, to provide grid stability. EV fast chargers can easily be controlled with little more sophistication than residential air conditioning and clothes dryers.

TOU and Demand Response are discussed here to complete the picture of control techniques for EV fast chargers—from advanced technical control to fiscal control.

## 4 Economics – Technology, System

In the world of technology many things are possible, but not all things are cost-effective. Many of the system components discussed here are currently in use, and thus have found a level of cost justification.

**Synchrophasors and PMUs.** PMUs have been installed worldwide and plans for the installation of more are expanding rapidly as the number of applications expands.

In the US, PMU planning, installation and application testing has preceded American Recovery and Reinvestment Act of 2009 (ARRA) stimulus funding, which implies even further that cost justification is solid.

**Active Transformers.** Likewise, power electronics compensation for wind farms, a catalyst for active high voltage transformer technology, is on the upswing and showing cost justification for that particular application. Will active transformers be able to demonstrate cost-effectiveness as a compensation enabler for EV fast chargers and grid-level energy storage? That will depend on silicon carbide transistor cost reductions and whether this technology can find enough application use to gain production quantity price reductions.

**Grid-Level Energy Storage.** Less certain is the prospect for the cost-effectiveness of grid-level energy storage. This technology is at the demonstration phase and major funding comes from the ARRA Stimulus package. Grid level energy storage has many potential applications of use to grid operators, such as frequency regulation, peak shaving and peak shifting. Of these, frequency regulation and peak shaving appear to provide the highest value. EV fast charger makes use of the peak shaving and grid stability aspect of energy storage.

As the cost of battery technology drops, primarily from quantity production of EV batteries, grid-level energy storage will become more cost-effective. However, other factors such as system round trip efficiency, cycle life and power capability play key roles in determining cost-effectiveness. One potential bright spot is the secondary use of EV batteries for grid-level energy storage. This has the dual benefit of lowering the total cost of the EV, while providing low cost batteries for the grid.

**EV Fast Chargers.** Much debate has focused on whether a business case can be made for EVs, let alone EV charger infrastructure. As time goes on, however, the prospect of peak oil looms, and the need for energy independence becomes critical. Political, social, and economic forces seem poised to push the business case for widespread EV adoption.

Several hurdles must be overcome to make this possible. Two in particular are (1) low cost, high safety, high cycle life battery technology, and (2) widespread, safe, grid-enabled EV charger infrastructure. The question of EV battery technology is the subject for another paper, but the prospects look quite encouraging with the advent of Nissan's LEAF™ EV and many other EVs from major Original Equipment Manufacturers (OEMs) coming to market.

Likewise, the prospects for charging infrastructure as a whole appear encouraging with the bulk of initial charger infrastructure coming to residences to enable overnight charging. Public EV charger infrastructure (both the charger and installation) is more expensive than residential and thought by many to be secondary to initial EV adoption. Without public EV charger infrastructure, however, conventional wisdom holds that widespread EV adoption is unlikely.

The economic case for EV fast chargers is a subset of public EV charger infrastructure. This is the most expensive equipment, the most expensive to install, and potentially the most expensive electricity. The business justification appears in many forms that include:

- Providing the ability of EV drivers to charge in thirty minutes or less (even as little as ten minutes)
- Revenue for the EV fast charger operator
- Advertizing for the EV fast charger operator
- A business attractor for the EV fast charger operator

EVs and their bi-directional chargers also can provide a major grid benefit in the form of highly distributed energy storage. This could enable the greater penetration of renewable energy, especially wind power, onto the grid, thus providing a large economic and grid stability benefit.

## 5 Conclusions

The technology to transform EV fast chargers, a grid load, into a valuable grid asset, exists in the form of components and a system approach that includes synchrophasors, active transformers, grid-level energy storage, Demand Response, and TOU pricing.

Already, PMUs and Demand Response are making great strides as key components to enable the Smart Grid paradigm. Electric utilities and EV stakeholders are conducting widespread demonstration programs and application testing for TOU pricing, grid-level energy storage, grid power electronics, and EV fast chargers.

In the coming years, many of the hooks are in place for the EV fast charge system approach to become commercial as the widespread adoption of EVs unfolds.

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