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Vehicle Charging as a Source of Grid Frequency Regulation

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Abstract

Electric power grids require that power generation and loads are in balance in order to keep the grid frequency constant. When there is an imbalance between the generation and load, the grid frequency will change. Grid frequency regulation is usually a service performed by powerplants that are controlled to vary their generation output up and down from a nominal value. Plug-in vehicles can provide a similar function by varying their charging rate based on locally-measured grid frequency. As plug-in vehicles reach large scale adoption, there is the potential for all frequency regulation to be provided through charging of plug-in vehicles.

Keywords: charging, power management, regulation, smart grid, V2G (vehicle to grid)

1   Introduction

Electric power grids are kept at nearly constant frequency only through active control of the balance of generation and load using the frequency-regulation ancillary service. The grid frequency continually varies in response to real-time imbalances of generation and load. Figure 1 shows typical frequency variation for the western grid interconnect in the United States over a half-hour period. Frequency regulation is conventionally performed by powerplants that contract with grid operators to allow their power output to be commanded in real time to vary the power output between upper and lower limits.

An additional source of frequency regulation is the governor function provided by conventional powerplants. The governor function (sometimes called "droop characteristic") provides an autonomous variation of generated power based on locally-sensed grid frequency. Generation is increased when frequency drops below the target value and decreased when frequency exceeds the target value. Powerplants usually respond relatively slowly to changes in desired power output [1], reducing the quality of regulation provided and often leading to the need to procure a larger amount of regulation capacity than would be needed if the response were faster.
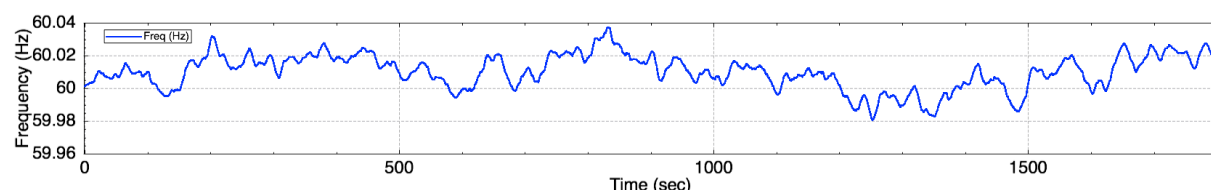

Figure 1: Typical grid frequency variation in the US western interconnect over a 30-minute period. (data collected by AV EVSE).

As renewable generation sources like wind and solar grow, this frequency-responsive generation is gradually decreasing. New sources of frequency regulation are therefore desirable.

2 Frequency Regulation with Storage and Load

Frequency regulation has usually been performed by powerplants that vary their generation up and down on command. Frequency regulation can also be provided by energy storage and loads. With energy storage, power is varied between an upper limit that delivers power to the grid and a lower limit that draws power from the grid. With load, regulation is performed by varying the load between maximum and a minimum load values.

Plug-in vehicles can be nearly ideal sources of frequency regulation since vehicles are generally being driven for only a small fraction of the time and have the potential to respond much faster than powerplants. The term V2G (short for Vehicle-to-Grid) was coined originally to refer to vehicles providing grid regulation services. [2]. Initially V2G applications focused on vehicles with bidirectional charging capability, which allows a vehicle to provide regulation continuously without ever fully recharging the battery pack. V2G regulation service has been successfully implemented and demonstrated by the University of Delaware and PJM [3].

There has been concern expressed by vehicle manufacturers and others that providing bidirectional V2G regulation services with vehicles has potential negative impact on vehicle battery life and could leave vehicle drivers with battery packs that are insufficiently charged for the driver's travel needs. In addition, providing bidirectional power flow from vehicles adds cost and complication to the charger hardware.

An alternative way to provide regulation from vehicles is as a variable load during charging. In this approach, the regulation dispatch commands cause the vehicle to vary the charging rate only. No additional cycling is seen by the battery pack -- only variable charging rate. Figure 2 shows an earlier demonstration of this approach using a Tesla Roadster [4]. The only impact on the charging process is that the average charge rate is reduced by approximately a factor of two (average current is midway between maximum and minimum current when providing symmetric regulation up and regulation down capacity).

A difficulty in providing conventional regulation ancillary service with vehicles is the amount of data interchange required. Regulation is typically dispatched on a 4-second update interval. This means that a dispatch command and acknowledgement may need to be sent to every vehicle every four seconds. There have, however, been developments to use advanced algorithms at the aggregator-level to significantly reduce the communications required per vehicle [5,6].

Another approach to reducing the communication overhead is to provide a regulation function based only on locally-sensed grid frequency. Conventional regulation is based on regulating a quantity called Area Control Error (ACE) to a zero target value. ACE is typically based on two components: the grid frequency error and the deviation from scheduled energy interchanges with neighboring control areas.

Since interchange error by itself is not indicative of a physical power imbalance on the grid, some grid operators have tested regulation services based on just grid frequency [7].
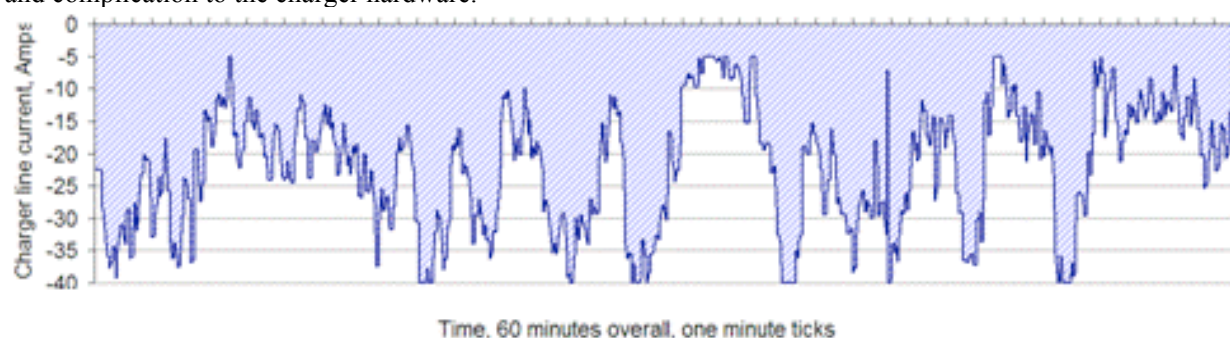

Figure 2: Grid regulation demonstration with Tesla Roadster during charging. AC line current vs time over a one hour period. AC line current of 22.5 Amps is the nominal point, with up/down capacity of 17.5A. From [4].

Such a frequency-based regulation service is nearly the same as a powerplant governor, or "droop characteristic." This suggests that a regulation-like service based entirely on locally-sensed frequency could be useful. Such a system was demonstrated with a bidirectional on-board charger by AC Propulsion in 2001 (figure 3) [8]. Recently frequency-only based control of loads has been the subject of academic research [9].
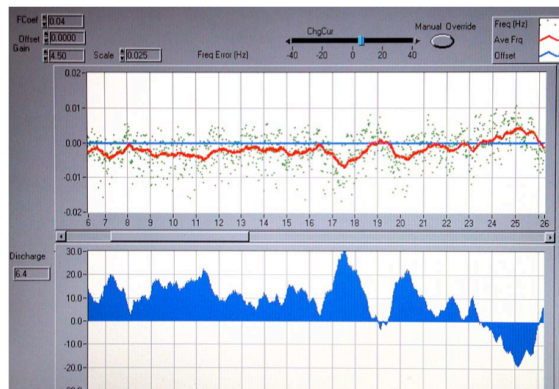

Figure 3: Vehicle bidirectional charging response to grid frequency error. Top graph (red line) is grid frequency; bottom graph is charger AC line current. (From [8])

3   Frequency-Responsive EVSE

3.1   Protoptype Frequency Responsive EVSE

A prototype frequency-responsive EVSE has been developed by AeroVironment (figure 4). The prototype EVSE is based on a standard EVSE-RS Plug-In EVSE, with software and hardware modifications added to enable the new functionality. A Bluetooth wireless serial port has been added for data logging, setting parameters, and controlling the operation of the EVSE for research and development purposes. The EVSE measures the local grid frequency to a resolution of 10 micro Hz at a one-second update rate and adjusts the vehicle charging rate based on the frequency deviation from the 60Hz target (and optionally based on the rate of change of frequency). The charging rate command is communicated to the vehicle once per second as the maximum AC line current available from the EVSE, using the standard PWM pilot signal as defined in SAE J1772^{tm}.

The EVSE is also set up to interrupt power immediately upon a sudden frequency drop,

indicative of a sudden loss of generation somewhere on the grid. The event is triggered by either frequency dropping below a prescribed target (typical value 59.94 Hz) or the rate of change of frequency exceeding a prescribed value. Charging is restored once the grid frequency recovers to the nominal value, with an additional small random time delay.

Figure 4: AV EVSE RS Plug-in with frequency-response capability.

3.2   Regulation   dynamic   range   and calibration

The smallest value of AC line current that can be commanded under the J1772 standard is 6 Amps. The dynamic range of AC current command is the difference between the maximum AC current and the minimum of 6 Amps. The maximum AC current could be limited either by the rating of the vehicle's onboard charger or by the maximum current rating of the EVSE. For example, the 2011 Leaf has a maximum input charging current of 16 Amps. The total dynamic range is thus $16 - 6 = 10$ Amps, or plus or minus 5 Amps from a nominal AC charge current of 11 Amps.

At exactly the nominal grid frequency of 60Hz, the charge current will then be 11Amps, or 2.64kW at 240V. The proportional gain of the system represents how much charging power varies per unit of frequency error. For convenience this gain has been expressed instead in terms of the value of frequency error that produces the maximum available change in charging power. After collecting hundreds of hours of grid frequency

data, a default value of 0.04Hz has been selected as being reasonable. The sensed grid frequency only rarely exceeded a deviation of 0.04 Hz from the 60Hz nominal value.

A vehicle with a 30-Amp capable charger again has a minimum current of 6 Amps, but has a larger nominal mid-point value of 18 Amps, and a range from the mid-point of plus or minus 12 Amps.

The EVSE needs to know the maximum charging current that a connected vehicle is capable of drawing in order to set the appropriate nominal value (e.g. 11 Amps for a vehicle with a charger capable of drawing 16 Amps). To accomplish this, a short automated calibration routine runs at the beginning of each charging session.

The average vehicle charge rate is of course reduced with frequency responsive charging. In the case of the 2011 Leaf, the nominal 16A (3.8kW) drops to 11A (2.6kW). Usually this poses no inconvenience at all as charging is usually complete well before the vehicle is needed, even at the reduced rate. For those occasional times when full-rate charging is desired, the EVSE is equipped with an override button.

3.3 Test Results

The EVSE has been tested with several electric and plug-in hybrid vehicles with good results. Figures 5, 6, and 7 show its operation with a BMW ActiveE electric vehicle. Figure 5 shows the grid frequency as measured by the EVSE over a 10-minute period. Figure 6 shows the corresponding maximum current command to the vehicle and the vehicle response. Most vehicles respond with AC line current in 1-Amp increments, leading to a "stair step" character in the line current profile. All vehicles tested have responded in less than 1 second, even though the J1772 standard allows up to 5 seconds.

Figure 7 shows the charging input power as a function of grid frequency. The discontinuous nature is due to the 1-Amp increments in line current mentioned above.

The frequency-responsive EVSE is now in use daily for charging the author's 2011 Nissan Leaf.
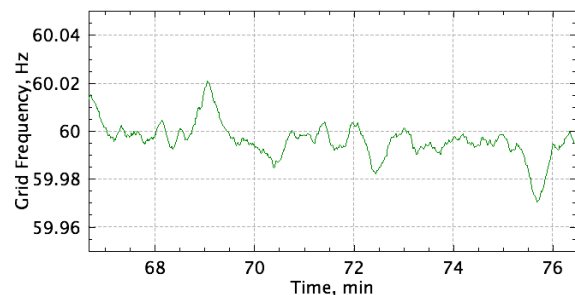

Figure 5: Grid frequency sensed by EVSE over a ten-minute period with one-second update interval.
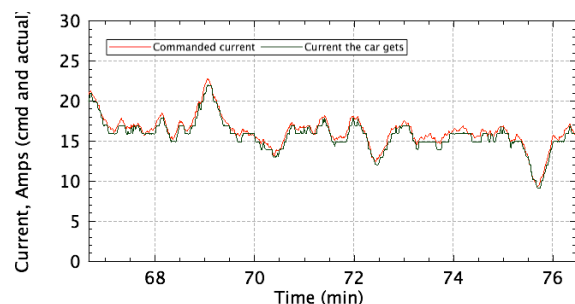

Figure 6: EVSE AC line current limit sent to vehicle over control pilot (red) and vehicle response (black, stair stepped).
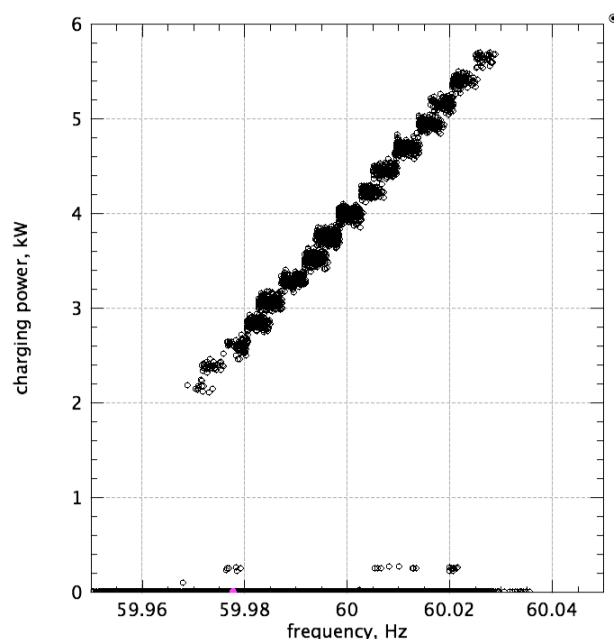

Figure 7: Vehicle charging power vs. grid frequency.

4 Future Potential

There is a real potential that in the future plug-in vehicles could play a major role in controlling the grid frequency. It is possible that all of the regulation frequency regulation on a grid could be

provided by plug in vehicles, freeing up powerplants to operate at constant power without the need for ramping up and down in response to frequency changes (either through their autonomous frequency-based droop characteristic, or through a grid operator's dispatched regulation commands). As an illustrative example, consider the grid in California, most of which is managed by the California Independent System Operator (Cal ISO). Cal ISO procures on the order of 400 MW of up and down regulation from powerplants. Consider instead the possibility that this regulation service were provided by the controllable charging load of plug-in vehicles. A basic calculation can illustrate the rough number of vehicles that would be required.

If 400 MW of up and down regulation is to be provided by loads, that means that the aggregate load must be capable of operating between zero and 800 MW. The average load would be 400MW. This represents daily energy consumed by the aggregate load of 24x400 or 9600 MWh. If, on average, electric vehicles consume 0.33 kWh per mile, then the 9600 MWh provides energy for 29 million vehicle miles. If each vehicle drives on average 29 miles per day, then 1 million vehicles could provide all of the regulation capacity (if the timing of recharging were coordinated so as to provide continuous regulation service during all hours of the day). To put 1 million vehicles into perspective, at the end of 2011 there were about 22 million registered cars in California.

Providing regulation ancillary service with load is arguably preferable to providing it with either generation or storage. With generation, powerplants are required to ramp up and down rapidly, reducing efficiency and increasing emissions [10]. Providing regulation with storage can mitigate these problems, but additional losses are created in shuttling energy in and out of storage systems. In addition, there is the cost of the dedicated storage system. With loads providing regulation, there are no additional losses – the load was going to be drawn anyway. Just the timing of the load is changed, and the only added costs are in the controls – the load already exists for another reason.

5   Conclusions

A prototype EVSE has been shown to be able to provide an accurate and fast frequency-response

charging function that provides a useful service to the grid that has some of the characteristics of conventional grid regulation and is like a high-quality version of a powerplant droop characteristic. The response of the system is significantly faster than the conventional regulation methods – on the order of 1 to 2 seconds from sensed frequency to the power change being completed. With widespread adoption of plug-in vehicles and managed charging start times, frequency-based charging has the potential to provide a large portion of the regulation service required on a power grid interconnection.

Acknowledgements

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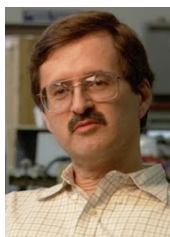
Alec Brooks is Vice President and Chief Technology Officer for the Efficient Energy Systems group of AeroVironment (AV). He has worked in the areas of electric vehicles and renewable energy while at AV, AC Propulsion, Tesla Motors, and Google. Dr. Brooks led the development of the GM Sunraycer and of the GM Impact electric vehicle, the forerunner of the EV1. He pioneered the concept of providing grid ancillary services from plug-in vehicles, and coined the term "V2G" to describe this capability. He has also developed smart charging approaches that can provide grid ancillary services. Dr. Brooks has M.S. and Ph.D. degrees in civil engineering from Caltech and a B.S. in civil engineering from UC Berkeley.