

**RIVER:
ROAMING INVERTER VEHICLE ENERGY RESOURCE**

by
Rodney Thomas Tyler McGee

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Rodney Thomas Tyler McGee

Approved: _____
Kenneth E. Barner, Ph.D.
Chair of the Department of Electrical and Computer Engineering

Approved: _____
Levi T. Thompson, Ph.D.
Dean of the College of Engineering

Approved: _____
Douglas J. Doren, Ph.D.
Interim Vice Provost for Graduate & Professional Education and Dean of
the Graduate College

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Fouad E. Kiamilev, Ph.D.
Professor in charge of dissertation

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Willett M. Kempton, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Charles J. Cotton, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

John V. Lawler, Ph.D.
Member of dissertation committee

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TABLE OF CONTENTS

LIST OF FIGURES	vii
ABSTRACT	viii
Chapter	
1 INTRODUCTION RIVER	1
2 CODES AND STANDARDS	5
2.1 Electrical Codes	5
2.2 OSHA	8
2.3 FMVSS	8
2.4 Background on Distributed Generation	10
2.5 IEEE 1547	11
2.6 UL 1741	15
3 SUPPLY EQUIPMENT	17
3.1 Background on EVSE	17
3.2 Communication between EVSE and the Vehicle	18
3.3 Digital Communication	18
4 THE GATEKEEPER	20
4.1 Origins of SAE J3072	20
4.2 Theory of the Gatekeeper	21
4.3 SAE J3072	24
4.4 Roaming Inverter Interconnection Process	25
CONCLUSION	26
BIBLIOGRAPHY	28

Appendix

- A BACKGROUND ON THE VEL AND VSL 30**
 - A.1 Vehicle Smart Link 30
 - A.2 Single Board Computer and Vehicle EVSE Link 31

- B COMMUNICATION OVER THE CONTROL PILOT 34**
 - B.1 Control Pilot and Proximity Detection 34
 - B.2 Replacing the PWM with Digital Data 35
 - B.3 Initial Internal Requirements 36
 - B.4 Negative Side Signaling 36
 - B.5 Improved High-speed CANBus Signaling 36
 - B.6 LIN over Control Pilot 37

- C BI-DIRECTIONAL CHARGER 40**
 - C.1 Rectifier 40
 - C.2 Inverter 40

- D AC OR DC 43**

LIST OF FIGURES

4.1	A system and Venn diagram covering regulatory and gatekeeper concepts	24
B.1	A near-complete EV and EVSE connected HS-CAN-CP circuit with PWM compatibility. Note the BSC RX and TX terminals connect to the CAN controller which is not shown.	37
B.2	This shows one side of the circuit at the top. The output is named Proposed Annex D and the bottom circuit is PWM and the output is labeled Annex A.	38
B.3	The red line shows the PWM for reference, and the blue line shows the large current spikes. The green line shows the high speed CAN and the mustard color shows the current which is lower during the switch because of the wave-shaping.	39

ABSTRACT

Electric Vehicles designed with bi-directional AC chargers allow the possibility of a flow of energy between an electric grid and the traction battery. Any device must go through a procedural interconnection process to be grid integrated.

The interconnection of so-called "behind the meter" inverters, or distributed energy resources, has dramatically increased since the introduction of IEEE standard 1547 in 2003. After that, devices like photovoltaic systems could be designed and tested to meet a single national set of base requirements. Fundamental to the installation and operation of these grid-tied systems is the assumption that they are fixed in place.

The interconnection of inverters on electric vehicles faces several major challenges. There are significantly different regulatory regimes, standards, and best practices in place for automobiles versus electrical installations. The configuration of an inverter is a location specific process, which is antithetical to the inter-state nature of a vehicle. This dissertation proposes a framework to solve the issues of interconnection of mobile distributed energy resources.

Chapter 1

INTRODUCTION RIVER

For the purpose of this dissertation, we will consider an electric vehicle containing a secondary cell battery and power electronics capable of bidirectional alternating current power flow both for locomotion and grid connection. How can this device which is inherently mobile be interconnected into an electric grid which is based on the assumption of stationary connections?

Briefly, we should establish the need for an interconnection process for these vehicles. Electric vehicles have a significant amount of energy storage and they are utilized for transportation on average $\frac{1}{20}th$ of the time; therefore, the remainder of that time they are parked and poetically usable for grid storage [15]. Beyond having vehicles connect to the grid for controlled charging, a bidirectional flow of power is usable for a much wider array of services [9] and is twelve times more valuable [22]. As more renewable generators are connected to the grid, more storage is needed [7] and vehicle based storage is lower cost than stationary dedicated storage [16]. But, as we will discuss there are complex techno-regulatory issues with vehicle-based roaming inverters.

In this dissertation, we will describe a framework of standards and policy for safely interconnecting vehicle-based grid-tied inverters. Vehicle and electrical systems sit within distinctly different technical and regulatory environments. RIVER (Roaming Inverter Vehicle Energy Resource) is a framework for the interconnection of these vehicle-based inverters through special Electric Vehicle Supply Equipment (EVSE). It is built around the same functional requirements as stationary distributed renewable generation but is designed to handle the problems associated with mobility.

This dissertation will not focus on environmental or economic aspects of public policy around interconnection. As implemented, the RIVER framework will be codified in multiple documents, national and state regulations, and industrial practices, not a single standard or document because the framework spans regulatory domains. Because we are focused on the concept of interconnecting roaming inverters into the AC grid, we will not discuss vehicles connected to an off-board inverter via direct-current link directly to the battery, which currently are mainly used for en-route charging. The dissertation will primarily cover the regulations in North America, since many of the relevant standards, are harmonized within Canada, Mexico, and United States of America.

Electric Vehicle Supply Equipment (EVSE) and the basic functions will be explained as background. As a quick introduction, today most passenger vehicles are charged at home using hand-inserted couplers between an AC mains connected EVSE and the vehicle inlet [11]. EVSE ensure ground continuity and monitor for ground faults. These charging stations signal to the EV indicating the availability and ampacity of power and provide a means for the vehicle to signal it is ready to energize. At a home in North America, single-phase continuous charging is either at 120V/12A using a portable EVSE that comes with the vehicle or by using a dedicated 240V EVSE with a current rating between 16A and 40A; although, up to 80A is achievable using the SAE J1772 coupler for AC charging. Destination charging at work or commercial locations is often provided through AC chargers at 208V. In 2018, SAE J3068 was published, which allows for three-phase charging at voltage and current levels beyond what is defined in SAE J1772. The base implementation of these charging standards do not allow for bidirectional flow of power, they only make accommodation for controlled charging.

Following that, we will cover the needed functions to make an EVSE an interconnection point for mobile inverters, also known as the gatekeeper. We will also discuss the other standards and regulatory areas needed as background to understand the RIVER framework.

Briefly, the technical standards and regulations discussed in this dissertation are:

- ANSI/UL standards, which primarily but not exclusively focus on the electrical safety of devices and components
- NFPA 70, which is also known as the National Electric Code
- IEEE Standards, primarily the 1547 series
- SAE standards, especially J3072

Tributaries of RIVER:

- **Electrical Equipment** consisting of a vetted bidirectional AC electric vehicle charging station installed in accordance with local and state codes with required gatekeeper functions. Existing systems are unidirectional.
- **Grid Interaction** of a vehicle-based mobile inverter operational characteristics of the inverter with the local grid and the protections provided by the charging station.
- **Information Exchange** establishing the parameters, settings, and bounds of operation each time a vehicle plugs into a charging station. For existing systems, this configuration is usually done once at the time of installation.
- **Dynamic Interconnection** is a high-level process allowing a combined system created by the connection of charging station and of different vehicle based inverters. Existing systems in contrast are a static system fixed in location. This new process is codified by public policy weaving together standards and local requirements.

In order to figure out if and how existing technical standards and regulations are adequate for a new paradigm or whether new standards are required it takes a deep and detailed understanding of both of the technical details and historical background of the standards and the laws and regulations that adopt and enforce them. Also it requires practical experience with how the existing devices are installed, tested, and operated.

The background here on the existing standards and regulations is equivalent to a literature review section. After years of learning and contributing to these standards, we ultimately decided to create a few where needed. We not only created new devices and prototypes but we went through the complete certification process for them. This,

if not unprecedented, it is at least exceedingly rare. Most people writing academic papers in engineering never understand or take the time to ponder how technical regulations will affect their creations and in the author's opinion it's one of the big reasons there is a disconnect between the academic and real world.

Chapter 2

CODES AND STANDARDS

In this section, we'll cover two types of requirements. One concerns the physical construction, design, and installation of devices. The other requirements are those placed on the system level behavior of devices that provide power to the grid. The National Electric Code, Underwriters Laboratory and Motor Vehicle Safety Standards provide many specific construction designs and testing requirements on particular devices and setups. While documents like IEEE 1547 describe the overall system performance of Distributed Energy Resources (DER). We'll look at the scope and background for these documents to understand how their work can be leveraged to create our framework for interconnecting roaming inverters.

2.1 Electrical Codes

In many countries, regulations governing the construction and installation of electrical infrastructure and equipment are adopted by the government. Sometimes these model regulations are created by international organizations, like the International Electrotechnical Commission, and adopted sometimes with modifications by nation states; this is a common practice in Europe. In the United States, an industry trade group called the National Fire Protection Association creates many model building codes, most notably NFPA 70: National Electrical Code.

Periodically, updated model codes are adopted by local and state governments. Others amend NFPA 70 or create their own regulations. This creates varied regulatory environments that need to be considered and addressed when developing a new paradigm of electrical interconnection.



Compliance with the local regulations is verified by persons representing the authority having jurisdiction, which include: fire marshals, building or electrical inspectors, and/or any local, state, federal, or military inspector. Sometimes, inspections are done periodically while others are done in response to an incident, complaint, or request. Most commonly, interactions with these authorities occur as a result of building new or modifying existing electrical installations. In particular interest for this dissertation are the installations required for bi-directional electric vehicle systems.

The 1996 edition of NFPA 70 included the addition of Article 625 entitled: "Electric Vehicle Charging System" under Chapter 6: "Special Equipment section". This was the first time the electrical code contained requirements for EVSE.



The 2005 edition of NFPA 70 added a section in Article 625 covering Interactive Systems after some conversations that Dr. Willett Kempton had with the committee maintaining the article. It defines a Utility-Interactive Inverter as: "An inverter intended for use in parallel with an electric utility to supply common loads that may deliver power to the utility"[6]. This means the Interactive Systems section would apply to an EVSE, which is connected to a grid-tied inverter.

The 2005 version of NEC Article 625, Interactive Systems section states:

Electric vehicle supply equipment and other parts of a system, either on-board or off-board the vehicle, that are identified for and intended to be interconnected to a vehicle and also serve as an optional standby system or an electric power production source or provide for bi-directional power feed shall be listed as suitable for that purpose. When used as an optional standby system, the requirements of Article 702 shall apply, and when used as an electric power production source, the requirements of Article 705 shall apply.

A plain reading of this section would imply that the vehicle must be listed. There is an important scoping issue with this requirement. A review of the scope for the entire NEC and the scope for Article 625 is necessary to understand the issue.

The NEC clearly states in NEC Article 90.2B:

”This Code does not cover the following: Installations in ships, watercraft other than floating buildings, railway rolling stock, aircraft, or automotive vehicles other than mobile homes and recreational vehicles.[12]”

Clearly, automotive vehicles are not covered by the NEC. Now, let us look at the scope for EVSE section:

Article 625.1 - Scope This article covers the electrical conductors and equipment external to an electric vehicle that connects an electric vehicle to a supply of electricity by conductive, inductive, or wireless power transfer (contactless inductive charging) means, and the installation of equipment and devices related to electric vehicle charging.[12]

This means the two higher level scoping sections indicates that the code does not cover installations in vehicles. However, in the scope of the previously stated Interactive systems sub-section of the 2005 version of Article 625, it is stated that there are NEC requirements for systems on-board the vehicle. This is in direct contradiction to the two other higher level scopes stated in the document and presented a conundrum about how to treat these bi-directional electric vehicles.

The 2017 NEC text of the Interactive Systems section of Article 625 was modified by a public comment from myself and several other colleagues to now read:

Electric vehicle supply equipment that is part of an interactive system that serves as an optional standby system, an electric power production source, or a bi-directional power feed shall be listed, evaluated for use with the specific electric vehicles, and marked as suitable for that purpose. When used as an optional standby system, the requirements of Article 702 shall apply; when used as an electric power production source, the requirements of Article 705 shall apply.

Informational Note: For further information on supply equipment, see ANSI/UL 1741, Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources, and ANSI/UL 9741, Bidirectional Electric Vehicle (EV) Charging System Equipment; for vehicle interactive systems, see SAE J3072, Standard for Interconnection Requirements for Onboard, Utility-Interactive Inverter Systems[10]

This new wording of the Interactive Systems section no longer puts requirements directly on electric vehicles. Instead it aims to ensure compatibility between the EVSE

and the electric vehicle. It also implies that an EVSE must be marked as suitable by the listing organization. The attributes that make an EVSE suitable will be discussed later in this dissertation.

2.2 OSHA

The regulatory environment is further confounded with the addition of the Occupational Safety and Health Act of 1970. The OSHA Act made a process for labs like Underwriters Laboratory (UL), Intertek, and Metlabs to become National Recognized Testing Laboratories (NRTL) who could test the safety of devices.



A listing from a NRTL is required by OSHA regulations for most electrical devices. Exempt from this in general are: Devices of electric utilities, planes, trains, and automobiles. In the Code of Federal Regulations, Title 29 Occupational Safety and Health, Standard 1910 - Sub-part S Electrical, Section 302 - Scope:

(a)(2) Not covered. The provisions of §§1910.302 through 1910.308 do not cover: (a)(2)(i) Installations in ships, watercraft, railway rolling stock, aircraft, or automotive vehicles other than mobile homes and recreational vehicles;[3]

Sections 303 - 308 are regulations covering wiring, protection, components, equipment, installation and use methods for electrical systems. These sections also contain the provisions that require the use of listed equipment tested by a nationally recognized testing laboratory and that it be listed for its specific use. These regulation imply a few important things:

- As electrical devices, EVSE must be listed by a NTRL in any environment where the NEC and/or OSHA regulations are in effect.
- Electrical installations on-board vehicle are not covered by these regulations

2.3 FMVSS

The problem then is how do we ensure the safety of an installation with connected grid-connection electrical devices with vehicles? Let us first review, who does have the broad authority to put safety regulations on vehicles.

Federal Motor Vehicle Safety Standards (FMVSS) are adopted and enforced by the National Highway Traffic Safety Administration (NHTSA) by the National Traffic and Motor Vehicle Safety Act of 1966, codified at 49 U.S.C. ch. 301. [2]. These regulations are the safety and performance requirements for motor vehicles or items of motor vehicle equipment. They cover the design, construction, or performance of motor vehicles, and is also protection against unreasonable risk of death or injury. Often, standards developed by SAE, the Society for Automotive Engineers, are incorporated in part or whole as FMVSS regulations. For example, §571.305 Electric-powered vehicles requirements discusses safety standards relating to electric shock. Typically the vehicle manufacturers complete first party testing for most of the systems on-board the vehicle.

Some third party tests are done for certain systems. Crash testing is a well-known type of third party test for automobiles conducted by outside organizations. A natural question that would arise is: why would we not require roaming inverters to be third-party tested? If UL does not have the authority to test vehicles, then the automobile third-party process could instead be followed. However, this solution does not capture the problem of roaming inverters sufficiently.

A roaming inverter has the added complexity of interacting with the local electrical configuration. It is not possible to test every inverter with every local electrical configuration that might be encountered by the roaming inverter. Furthermore, it is not possible to trust the roaming inverter because there is no viable way to inspect (for example, visually verify the NRTL mark) each vehicle at the time of plug-in. It should be noted that at this time, non-grid-tied inverters, e.g. emergency generators, do not need to be listed. This is a compromise between the needs for electricity during an emergency and the safety benefits of tested electrical equipment.

So, while federal mandated safety standards for automobiles exist, a more robust solution where the trust is placed in a stationary, installed, and safety compliant EVSE is the natural answer. In this way a roaming inverter that is untrusted by the local installation can interconnect with, and if necessary forcefully disconnected by a trusted device. This concept is discussed in chapter 4.

2.4 Background on Distributed Generation

One of the tributaries of RIVER mentioned in the introduction was the operating characteristics of the inverter. The inverters grid compatibility is a complex interaction of the inverters operating characteristics and behaviors. The creation of IEEE 1547 has allowed millions of distributed energy devices to connect to the local electrical grids. To understand how IEEE 1547 fits into the vehicle based mobile framework in this dissertation a historical view of the creation of IEEE 1547 is useful.



This section covers the evolution of the requirements for these devices from a loose set of recommended practices to a single standard codified into U.S. law. The documents that will be reviewed include: the Public Utility Regulatory Policies Act of 1978 – which formalized the idea of distributed generation, the Electric Consumers Act of 1986 – which requires that standards for interconnection have a basis in safety and reliability, IEEE – which makes the recommended practices and standards, and finally the 2005 Energy Act that codifies IEEE 1547 standards into U.S. Law.

The Public Utility Regulatory Policies Act of 1978 (PURPA) was the first step towards distributed generation. The law allowed the Federal Energy Regulatory Commission, reconstituted from the Federal Power Commission (FPC) in 1977, to issue orders concerning the interconnection of small generators. These qualified facilities would need to conserve energy, reduce cost, or improve reliability. It should be stressed that distributed generation was allowed to interconnect because it was supposed to improve one of these particular areas. PURPA was the birth of distributed generation and it confirmed States had the power to make additional rules about distributed generation.

The interconnection must be in the public interest, but also not result in uncompensated economic loss, undue burden, or reduce reliability. Also the qualifying facility must pay their share of incurred cost including feasibility studies and enlargement of transmission equipment.

2.5 IEEE 1547

So while PURPA enabled some distributed generation under its auspices, it directly created a large varying patchwork of procedures across the country for these types of interconnection. This issue is well-described in a FERC issued staff paper RM79-55[1], debating rules they would later issue, which argues that there existed a great deal of regulatory uncertainty for these interconnection arrangements which have "fallen into a gap between FERC and State regulators." The commission states "we will not attempt to provide in all instances a single correct or even preferred approach to implementation".

The 1986 amendments to the Federal Power Act, entitled the Electric Consumers Protection Act (ECPA), in 18 CFR §292.308 states:

Any State regulatory authority (with respect to any electric utility over which it has ratemaking authority) or non-regulated electric utility may establish reasonable standards to ensure system safety and reliability of interconnected operations. Such standards may be recommended by any electric utility, any qualifying facility, or any other person. If any State regulatory authority (with respect to any electric utility over which it has ratemaking authority) or non-regulated electric utility establishes such standards, it shall specify the need for such standards on the basis of system safety and reliability.

Also stated in 18 CFR §292.309, the obligation to purchase from qualifying facilities was set to be terminated in 2005, about 20 years after the act. Interconnection of customer owned generators is reaffirmed by the Energy policy act of 2005 [17].

Two years after IEEE 1547 was first published, it was adopted as nationally as a basis for all interconnection in the 2005 Energy Act. Also in that year IEEE 1547.1 was published; it documented the testing procedures for the main 1547 standard. From Section 1254 of the 2005 Energy Act:

(a) ADOPTION OF STANDARDS. Section 111(d) of the Public Utility Regulatory Policies Act of 1978 (16 U.S.C. 2621(d)) is amended by adding at the end the following:

(15) INTERCONNECTION. Each electric utility shall make available, upon request, interconnection service to any electric consumer that the electric

utility serves. For purposes of this paragraph, the term “interconnection service” means service to an electric consumer under which an on-site generating facility on the consumer’s premises shall be connected to the local distribution facilities. Interconnection services shall be offered based upon the standards developed by the Institute of Electrical and Electronics Engineers: IEEE Standard 1547 for Interconnecting Distributed Resources with Electric Power Systems, as they may be amended from time to time. In addition, agreements and procedures shall be established whereby the services are offered shall promote current best practices of interconnection for distributed generation, including but not limited to practices stipulated in model codes adopted by associations of state regulatory agencies. All such agreements and procedures shall be just and reasonable, and not unduly discriminatory or preferential.

In summary:

- Electric utility have to make an interconnection but they make their own procedures and agreements
- Allows additional state and local rules to apply based on best practices and model codes
- Interconnection must be reasonable and not biased

The IEEE standards development process is organized through a series of coordinating committees. IEEE 1547 (IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems) grew out of two existing standards IEEE Standard 1001 and IEEE Standard 929.¹

IEEE Standard 1001 (Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems) was developed under SCC23 (Standards Coordinating Committee 23 on Dispersed Storage and Generation). Approved by IEEE as a Standard in June 9, 1988 and approved as an ANSI standard in 1989, published as ANSI/IEEE Standard 1001-1988. This standard covered all types of distributed generation and storage, and concerns itself with the installation issues like location of disconnects and meters and other basic design consideration.

¹ There is a similar standard to IEEE 929 called IEEE 1021-1988 - Recommended Practice for Utility Interconnection of Small Wind Energy Conversion Systems

IEEE Standard 929 (IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems) was developed under SCC21 (Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage). According to IEEE, Standard 929 was created in response to PURPA. The first version was approved by the IEEE Standards Board on December 11, 1986 and approved as a ANSI standard on May 18, 1987, the standard was published as ANSI/IEEE Standard 929-1988. It is a relatively short standard and contains only two pages of technical requirements. It does, however, contain several "shall" requirements:

- Service voltage and frequency: "The photovoltaic system voltage shall be compatible with the utility" and "The PV system shall operate in synchronism with the utility"
- Loss of utility voltage: "The PV system shall disconnect from a de-energized distribution line irrespective of connected loads or other generators"
- Over / Under Voltage and Frequency: "When the interface voltage deviates outside the range for longer than 2 s, the photovoltaic system shall disconnect from the utility."
- Utility Recovery: "Following system disconnects the photovoltaic system shall remain disconnected until utility service voltage has recovered for a sufficient period of time, typically 30 s to 2 min."
- Direct-Current Isolation: "The PV system shall not inject DC into the AC interface under normal or abnormal conditions"
- Grounding: "The PV system and interfacing equipment shall be grounded in accordance with applicable local and national codes"
- Lighting and Surge Protection: "The photovoltaic system shall have surge protection in accordance with applicable local and national codes"

IEEE 929 has the following should requirements:

- Flicker: "The operating of the PV system should not cause excessive voltage flicker on the utility".

- Harmonics and distortion: "In general, the operation of the photovoltaic system should not cause excessive distortion or result in excessive injection of harmonic currents." ²
- Power Factor: "With on-site loads disconnected, the PV system should have a power factor greater than 0.85"
- Manual disconnection: "a lockable and accessible manual load break disconnect switch should be provided"

There is a major shift in the intent between IEEE 929/1001, which is a recommended practice and IEEE 1547 a standard. One example of these, is the change of stance on the requirements for harmonics, over/under voltage, and other parameters. In 929, the suggestion was check with the local utility about their rules but in 1547 these become nationally uniform requirement which would streamline the design, testing, and installation of distributed generation.

IEEE 929

This recommended practice contains general recommendations for interfacing photovoltaic systems with the electric utility. Since utility systems and practices may vary from location to location, the photovoltaic system owner should consult the local utility company as to its specific requirements. Current practice is for utilities and customers to address the technical concerns prior to interconnection and the resolve subsequent problems as they arise. At present there is insufficient data available to provide a basis for a national consensus standard on harmonics.

IEEE 1547

There is a critical need to have a single document of consensus standard technical requirements for DR interconnection rather than having to conform to numerous local practices and guidelines. This standard addresses that critical need by providing uniform criteria and requirements relevant

² The standard notes there is no national consensus on flicker and harmonics; however, in a footnote for harmonics notes the following: Suggested future design targets for voltage and current harmonic limits given in EPRI AP/EM-31241983, [3]: are 5% current total harmonic distortion with a 3% maximum for individual current harmonics, and 2% voltage total harmonic distortion with a one percent maximum for individual voltage harmonics. These values are generally applied at the peak output rating of the system.

to the performance, operation, testing, safety considerations, and maintenance of the interconnection. The intent of this standard is to define the technical requirements in a manner that can be universally adopted. The universality relates not only to the technical aspects, but also to the adoption of this standard as being pertinent across a number of industries and institutions, e.g., hardware manufacturers, utilities, energy service companies, codes and standards organizations, regulators and legislators, and other interested entities.

The publication of IEEE 1547 clearly attempted universality while IEEE 929 did not target and eschewed it in favor of rules that varied by location and local utility rules. In fact, it discourages any local rules that interfere with the standard.

This standard provides the minimum functional technical requirements that are universally needed to help assure a technically sound interconnection. Any additional local requirements should not be implemented to the detriment of the functional technical requirements of this standard[5]

2.6 UL 1741

Earlier in this chapter, we established the requirements for electrical installations and devices. Typically these involve rules based on the National Electrical Code and devices tested by a Nationally Recognized Testing Laboratory to ANSI/UL standards. UL/ANSI 1741 is a typical example of how these documents tie together devices, installation, and in this case the behavior and functions of a PV inverter. This is device follows a well-established regulatory pathway which neatly fits into the existing regulatory regime.



From the scope of ANSI/UL 1741:

1.1 These requirements cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in stand-alone (not grid-connected) or utility-interactive (grid-connected) power systems. Utility-interactive inverters, converters, and ISE are intended to be operated in parallel with an electric power system (EPS) to supply power to common loads.

1.2 For utility-interactive equipment, these requirements are intended to supplement and be used in conjunction with the Standard for Interconnecting Distributed Resources With Electric Power Systems, IEEE 1547, and

the Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems, IEEE 1547.1.

...

1.5 The products covered by these requirements are intended to be installed in accordance with the National Electrical Code, NFPA 70.

UL 1741 has specific construction requirements and tests associated with it which are incompatible with automotive systems, for example, how the device should be fixed in place and attached. UL documents derive their relevancy from the electrical codes and laws, like OSHA it can tie all of these documents together because they are all coming from the same regulatory structure.

But 1741 also doesn't have the idea of two things coming together and forming a new system. UL 1741 and its ilk are concerned mostly with not causing unsafe electrical appliances and installations that may cause death or harm to individuals. Motor Vehicle standards are designed to make sure that vehicles are safe. Unfortunately, neither of these regulatory pathways in and of themselves is sufficient.

Chapter 3

SUPPLY EQUIPMENT

3.1 Background on EVSE

EVSE stands for Electric Vehicle Supply Equipment. EVSE are the collection of conductors, connectors, plugs, cords, fittings, power outlets, devices, and other equipment that are used with the specific purpose of delivering energy between the premises wiring and the electric vehicle.

In this chapter, we will only be discussing EVSE that deliver AC power to the vehicle because only these types are used with vehicles with on-board inverters. In North America, EVSE are listed to UL/ANSI 2954 and its equivalents in Canada and Mexico. There are two other sub-standards which relate: UL/ANSI 2231, which covers equipment to protect persons using the charging stations, and UL/ANSI 2251, which cover the cord-sets, inlets, and connectors for electric vehicles. While many EVSE are cord-and-plug connected to an outlet of the premise wiring, SAE standards for bidirectional EVSE require the unit to be permanently wired. So for the purposes of this chapter, we will be discussing fixed (non-portable), permanently-wired, alternating-current EVSE.

This device, like the solar inverter, and unlike components on the electric vehicle, is covered by regulatory pathways that serve electrical devices. The EVSE installation is done in accordance with local rules and regulations and connected to a particular place within the grid.

The two primary safety functions of a charging station are protecting against ground faults (called a CCID 2231) and ensuring ground continuity. EVSE based on SAE standards ensure ground continuity using the Control Pilot. This circuit

additionally has states which ensure the following: verification of vehicle connection, EVSE ready supply energy, EV ready to accept energy, determination of ventilation requirements, and EVSE current capability. In summary, the Control Pilot enables the charging station to only supply power to the vehicle when the vehicle is connected, wants charge, and keeps it charging within safe parameters.

Many EVSE have extra functions, which are not required, such as supplementary over-current protective devices or energy metering. In order to only supply energy to the vehicle, when connected, the EVSE has a contactor which interrupts the AC grid connection. These functions could be combined, such as detecting an abnormality in the flow of power, and interrupting the power to the vehicle by opening the main contactor in the EVSE. An example might be when you have an energy meter in the EVSE the contactor could be opened when uncoordinated reverse power flow is detected by leveraging the metering current measurement.

3.2 Communication between EVSE and the Vehicle

The baseline EVSE functional requirements require some degree of communication or signaling between the vehicle and itself. These basic implementations described in standards like SAE J1772 are neither digital nor extensible by themselves. The analog PWM control pilot described in Annex B can only signal the availability of a certain amount of power expressed in amperes, and the vehicle can signal whether it is ready for that certain amount of power at this time. Although, new standards like SAE J3068 have digital communications in its basic form by utilizing LIN-bus; this is described in [Appendix B](#).

3.3 Digital Communication

Beginning in late 2009, we started working on the design of a digital communication system that would be used in our new charging station. These new hardware and communication protocols were developed for our vehicles participating in the fast

responding application. Internally, we designed a CANBus over control pilot for supporting digital communications and bi-directional AC power flow through a J1772 connector. This provided us with robust association between the vehicle and the supply equipment; it was also able to carry Internet protocol data over this link used for high level authentication and encryption. Complete association and start of charging occurs in under one second from initial plugin.

We began participating in standardization committees, focusing on communication between the electric vehicle and the supply equipment. We began to actively engage in the Society for Automotive Engineers (SAE), the International Electrotechnical Commission (IEC), and International Organization for Standardization (ISO). In late 2012, we learned a similar communication approach was being developed into a standard in the IEC. Since then we have contributed heavily and have harmonized our approaches into the third edition of IEC-61851-1 Annex D. The system uses LINBus over the control pilot and is backwards compatible with existing PWM signaling. Currently Annex D is focused on AC energy supply, but it could be used on any system with a control pilot.

Chapter 4

THE GATEKEEPER

During the demonstration of vehicles with reverse power flow here at the University of Delaware, I started to follow and contribute to some relevant standards. Our group started discussing communication requirements for the frequency regulation use case and other interconnection issues with inverters on-board vehicles. I gave a general overview of our project with the participants of the SAE Hybrid Communication and Interoperability Task Force chaired by Richard Scholer.

During SAE 2847/3 standards meetings lead by Hank McGlynn on April 25, 2013 and May 16, 2013, I gave presentations on the hardware and software components and overall architecture of our PJM frequency regulation project at the University of Delaware. Our EVSE was an important component in the system which facilitated the interconnection of vehicles with on-board inverters. It was intelligent and it only allowed vehicles which had been tested for anti-islanding to back-feed into the grid.

Importantly, this was in contrast to the model, which initially envisioned a Distributed Energy Resource (DER) on a Plug-in Electric Vehicle (PEV) which would function with any EVSE including those which were dumb, meaning they were not capable of high-level communication. In other words, the PEV would have all the intelligence and could seamlessly interconnect and communicate to facilitate back-feeding into the grid without the EVSE being involved.

4.1 Origins of SAE J3072

During these meetings, in response to a question about whether it was necessary to have an EVSE with software that communicates with the vehicle, I responded by

asking another question: "How could the inverter calculate the voltage limits (as required by IEEE 1547) without knowing the nominal voltage of the EVSE?" The EMS (Energy Management System) cannot store this parameter for use by the currently connected vehicles in the household, because even within a typical home there are two system voltages: 120 and 240VAC. In commercial applications, there are more nominal system voltages. The chairman Hank McGlynn, Ted Bohn, and I discussed other possible solutions, such as measuring voltage and estimating upon initial plug-in, but 208VAC and 240VAC overlap with each other within a +/- 10 % variation. Another idea discussed was a database of EVSE reference voltages and other interconnect information on the EMS that the PEV could access, but even that required some association between the EVSE and EV. These alternatives would still require a modified EVSE for the PEV to perform DER services.

In the end, the consensus from the discussions was that an intelligent EVSE with association would be part of the whole DER system for a roaming inverter. I also had many private discussions with Hank McGlynn about how the demonstration project got interconnection where I discussed in more depth how our EVSE acted as gate-keepers to the grid. From our discussions, Mr. McGlynn and I thought there was a need to formalize this roaming inverter system architecture in a document.

In early 2014, the Task Force officially started work on a second version of a document called J2836/3: PEV Communicating as a Distributed Energy Resource. By reopening J2836/3 it would allow us to schedule meetings to discuss the issues with the roaming inverter. The key issue would be the interconnection process. From these meetings, we established the need for a new document that described the requirements to interconnect a roaming inverter, which once approved by the SAE EV Hybrid committee, was assigned the number J3072.

4.2 Theory of the Gatekeeper

In May 2007, the University of Delaware and its other partners established the Mid-Atlantic Grid Interactive Car Consortium (MAGICC) to prove that vehicles could

provide grid services. In October 2007, MAGICC started grid back-feeding from EVs based on a real control signal. Back then, the system did not use a modern EVSE that could act as a gatekeeper. In late 2009, I starting working on a project to build a bidirectional EVSE which used stored parameters on the EV, and EVSE were used determine the suitability for reverse power-flow based on a exchange of parameters during the initial plug-in handshake. This is described in column 10 line 21 of our patent [14] on EVSE for grid-integrated vehicles.

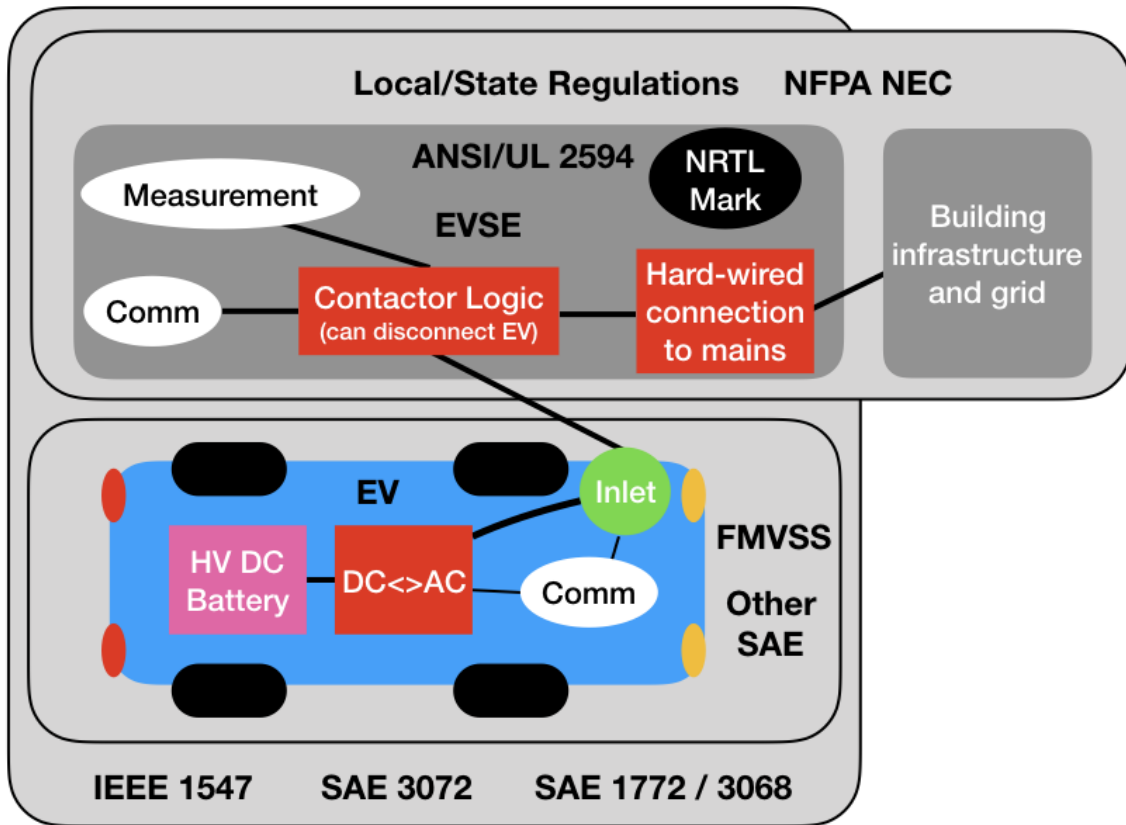
Based on our new safety model described above, we argued for changes in NFPA 70, the 2017 National Electric Code, in Article 625 Interactive System section. The new text states that EVSE that are part of a system that provides a bidirectional feed must be listed and marked as suitable for that purpose. In practice for the vast majority of situations in the United States, this means the EVSE must be listed by an OSHA NRTL, for example UL, and be marked something to the effect of: "FOR BIDIRECTIONAL USE." The interactive systems section of 625 also requires that the EVSE be: "evaluated for use with the specific electric vehicles." These requirements gave us another regulatory affirmation for the EVSE to be a trusted gatekeeper. In this case, trusted means evaluated and listed by an organization recognized by the authority having jurisdiction on electrical equipment safety.

Also discussed in chapter 2, vehicles are regulated by a completely different regulatory pathway. The OSHA NRTL listing requirement for electrical devices does not apply to equipment and installations on-board trains, planes, and automobiles. Electrical installations on general-purpose vehicles are out of the scope of the national electrical code. Any system which proposes a method to safely interconnect roaming inverters on electric vehicles must sufficiently handle the incongruity between the two devices and their very different sets of technical and regulatory standards to the satisfaction of both industries. For example, without sufficient confidence in a system for interconnecting vehicle-based resources, the electric utilities cannot create a streamline process for massive adoption. Likewise, without a straightforward path to interconnection, OEMs cannot invest in modifications to make their vehicles bidirectional.

The traditional process is not viable in a more fundamental way. First, consider the typical process for a solar inverter or any fixed, permanently-installed piece of equipment. A local inspector and/or utility worker could look at the name plate on the inverter and check for a recognized mark from a NRTL, signifying compliance with ANSI/UL 1741. Because 1741 requires compliance with IEEE 1547 using a normative reference, we then can ensure, as 1741 calls it, "utility compatibility." This process of verifying equipment at the time of installation is clearly not viable for automotive equipment, due to its inherently mobile nature. Even if we were to have inspectors verify particular vehicles interconnected through EVSE, it is unreasonable to expect the vehicle to be always plugged in at that location and for no other vehicles to use the same charging station. The gatekeeper concept is to verify at the time of each plug-in that the particular vehicle is compatible to the specific requirements of this grid location, which are part of a J3072 bidirectional EVSE. Communication to ensure compatibility continuously is a significantly stronger model than the one-time check at time of installation model.

Because the EVSE is local and permanently installed at a particular grid location, and is fully held accountable under the same regulatory framework as any other piece of electrical equipment, it is well-suited to protect the interests of the grid. Importantly, the EVSE can provide secondary but trusted enforcement of anti-islanding (using passive detection), voltage limits, frequency bounds, and power quality requirements. This means we can instead continuously verify compliance and open the contactor when the vehicle goes outside of allowed range of operation. This is similar to an interconnection safety relay. In this way, from the perspective of the electrical device safety regime the vehicle does not need to be trusted. Communication can allow the vehicle to know the bounds of operation which will keep the vehicle connected to the grid and within the agreed bounds of operation.

Figure 4.1: A system and Venn diagram covering regulatory and gatekeeper concepts



4.3 SAE J3072

The most unique aspect about SAE J3072 [4], is that through communication, the parameters and requirements to interconnect a certain vehicle inverter type at a particular EVSE grid location are exchanged. The standard defined requirements for all the site-specific settings to be transferred to the electric vehicle when it connects.

SAE J3072's scope was to provide the requirements for interconnection for an electric vehicle with an on-board inverter. Importantly this included the communications required to verify and configure the vehicle for discharge into the grid. Like UL 1741, SAE J3072 does not itself contain the tests for anti-islanding or overall grid compatibility. Instead, a nominal reference is made to IEEE 1547 requiring testing and compliance.

J3072 states the challenge this way:

However, a roaming PEV inverter creates some unique technical and interconnection approval issues. J3072 is intended to deal with both. The PEV can easily cross utility service areas and state lines and interconnect at locations with different site settings.[4]

4.4 Roaming Inverter Interconnection Process

SAE J3072 outlines an interconnection process where an application for interconnection would include an EVSE model configured for the particular location, but importantly is not associated with one particular electric vehicle. Recalling that the NEC requires the EVSE to be "evaluated for use with the specific electric vehicles", there is testing needed to ensure that the charging station conforms to SAE J3072. J3072 also allows the charging station to hold a list of Inverter System Model numbers which are compatible at that location and only authorize those vehicles for reverse power flow.

J3072 suggests that: "Utility DER interconnection application and approval procedures will need to be modified to allow for roaming PEVs with onboard inverters". To that end in 2019, Delaware modified state law to allow SAE J3072 to be used for the interconnection. The act was titled "AN ACT TO AMEND TITLE 26 OF THE DELAWARE CODE RELATING TO GENERATING SYSTEMS WITH THE NEW SOCIETY OF AUTOMOTIVE ENGINEERS ELECTRIC SAFETY STANDARD." This adoption allows a streamlined process for interconnecting vehicles in Delaware like that is available to solar inverters! A similar rule-making processes are ongoing in multiple states at this time.

CONCLUSION

In this dissertation, I have detailed the creation of a new way to safely interconnect roaming vehicle-based inverters. This was based on what we learned during our conceptualization, design, implementation, and market operation of such systems over several years. During the course of our many research projects and demonstrations, standards were altered, like the National Electric Code, and others were created, like SAE J3072. Other standards were also created, like SAE J3068. Electric vehicles, and more so heavy vehicles with three-phase power based on SAE J3068, are particularly valuable if leveraged for grid storage because of their high power level. This standard was created by the SAE Medium and Heavy Duty Conductive Power Transfer Task Force that I led as chairman. We also filed for a patent on the bidirectional charging station with the ability to store electrical parameters of the grid and to receive parameters from whichever EV is plugged in for the charging or V2G session [14].

One of the unique aspects of our approach is that we developed a solution without insisting that one of the parties, either the automotive or electrical world, adopt the others' regulatory view. We designed electronics and software for both EVSE and vehicle systems, and this gave us unique insight into what is a cost- and regulatory-optimized system design. It may surprise some that design of both EV and EVSE sides is almost unheard of in this industry. Rather, electric equipment companies design the chargers and OEMs design the EVs, the two working together only because of common standards (and testing). One tendency of the prevailing practice of not designing for the overall system is to push cost and complexity to the other side. An example of this is OEMs that are advocating using a DC connection to the vehicle for all advanced applications. This increases the cost of bidirectional systems, as discussed in Appendix D.

The other distinguishing characteristic of this work is that both standards and state laws have been completed and passed into effect, informed by my technical work with the help of the rest of the EV group. I myself have been a member of the technical committees, have generated new topics for standardization, and have chaired the technical committees. Policy specialists in our EV group, informed by our technical work and standards, have passed laws approving these standards and practices. As mentioned in the introduction, there is a need for more storage as the grid becomes composed of more renewable generation. If the electrification of transportation is coupled with a straightforward and inexpensive process for interconnecting vehicle-based storage, we could lower the burden on ratepayers for the changes to the grid. That is why this work includes technical and regulatory changes to facilitate this technology.

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- US Department of Energy, Vehicle to Grid Demonstration Project, DE-FC26-08NT01905
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- National Renewable Energy Laboratory, Open V2X at ESIF, NCS-42326-05
- NRG Energy Inc, eV2G Research Development and Demonstration
- Nuvve Corp, Grid Integrated Vehicles and Aggregation Server
- MIT Lincoln Labs, EVSE and VSL Demonstration Project
- Honda, Accord V2G Demonstration Project
- BMW, Mini E V2G Demonstration Project
- Milbank Manufacturing Company, EVSE Development Project
- University of Delaware's Office of Economic Innovation and Partnerships

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Appendix A

BACKGROUND ON THE VEL AND VSL

A.1 Vehicle Smart Link

The VSL, or Vehicle Smart Link is the primary component allowing a vehicle to be grid integrated. It handles communication between the EVSE and the vehicle and performs the following functions:

- On-board intelligence about driving needs
- Electrical constraints
- Agent (from multi-agent systems [13]) that acts in the interests of the vehicle driver
- Negotiates availability for market dispatch
- First priority being the vehicle being used to drive
- A variety of different OEM systems
- EVSE network connection to Vehicle (via control pilot)
- Connection to OEM systems (generally CANBus)

The VSL on-board the vehicle extracts relevant data about the vehicle capabilities, power available, energy needed for the next trip, and environmental conditions. The VSL can also provide services such as load management, controlled charging, or emergency power, but the value is different for each of these services. The software for the VSL can be adapted to an OEM-specific system using the VEL.

The aggregator, which is a server aggregating many resources into larger groups, takes an associated EV/EVSE pair and provides energy services. Intelligence and controls are needed in the vehicle, charging station, and centralized aggregator to communicate with the power grid operator. Most solutions by either OEMs or charging station

vendors put all the intelligence on one side, which either violated regulatory/safety requirements or cannot produce maximum value for energy services. While the term VSL is normally used in the context of the vehicle itself, it is present in all of our intelligent charging stations. The two primary components of the VSL are the Single Board Computer (SBC) and the Vehicle EVSE Link (VEL).

A.2 Single Board Computer and Vehicle EVSE Link

The higher level hardware and software on the VSL is currently implemented as an SBC, or single board computer, with an ARM SoC, system on a chip, combined with an FGPA. It is running the agent code on a full-featured embedded Linux. It is manufactured by Technologic Systems and the model number is TS-7500, or more recently the TS-7600.

The VEL board is the low-level intelligence designed around a single micro-controller. One of its primary functions is the implementation of signaling over the control pilot and handling the plug proximity signal. A non-obvious design consideration is that many functional blocks are duplicated in the EV implementation and the EVSE implementation.

The device implements PWM-CP or pulse-width modulation on the control pilot, a widely used and substantially limited protocol defined in conductive charging standard SAE J1772 first issued in October 1996 and substantially revised in 2010. Minor differences between implementations of the protocol lead to various levels of incompatibility, especially for complex use cases related to vehicle sleep or wake-up. The system is also standardized in IEC 61851-1 Annex A with some differences.

The 5.2B version of the VEL was the first production revision. The board was assembled by Shore Circuits in Eatontown, New Jersey. Prior versions were assembled by hand in a process that took many man-hours but was useful for early research and development.

The VSL is designed to run off of a nominal 12 volts. In an electric vehicle, while it may be more stable, generally the 12V rail in a car is very noisy. There may

be some large voltage fluctuations containing high-frequency noise that will penetrate through voltage regulators causing noise on internal rails. To mitigate these issues, we use filters in a PI configuration. On the EVSE though, while the power is cleaner, there are events, such as switching the main relay, that might cause the 12-volt rail to go out of regulation.

In the earlier implementations of the board, we used only DC-to-DC converters based on low dropout regulator topology, often called LDOs. While LDOs are often very simple, usually only requiring a few capacitors, they can dissipate a lot of heat. The voltage drop in the LDO (V_{in} minus V_{out}) multiplied by the current is the power that you dissipate in the LDO. So a 12 volt system with 3.3 volt micro-controller utilizing an LDO would provide no more than a 27% percent efficiency. All that lost power is dissipated in a single power converter chip. So it became prudent to include a DC-to-DC converter utilizing a switching architecture to increase efficiency. We chose to use a Texas Instrument Swift DC-to-DC, model TPS54426, adaptive mode synchronous buck converter. It can provide several amps, has a low quiescent current, and good load efficiency.

The VEL is also responsible for providing the 5 volt power to the SBC. The current implementation board draws approximately 400 mA at 5 volts. The power consumption of the VEL board itself is typically around 50 mA while operational, and around 1 mA while in sleep mode. Powering a larger load like the SBC board with an LDO regulator to supply power would generate approximately 3 watts of waste heat. All other power rails are derived from this 5V rail. Power to the SBC and to the dual output LT1945 DC-to-DC are switched through Diodes Inc model AP2162/AP2172 intended for powering USB loads, and are the micro-controller.

The LT1945 chip provides regulated positive and negative voltages for the control pilot (+/- 12V). Unlike the input power, which is nominally 12 volts, these supplies should be tightly regulated as it powers pilot signal produced by the EVSE, which must be accurate. One issue that came up when prototyping this power converter based on the Linear LT1945 was a startup power issue. If powered from a current-limited voltage

source the input voltage would collapse, leaving the digital control logic dysfunctional, and leaving the main switch in the converter closed, causing a thermal event destroying the chip. To fix this we added an RC-delay circuit on the shut down pins, so when the chip was powered up, it allows plenty of time for its capacitors to charge up before the chip actually starts switching to generate plus and minus pilot voltages.

The analog switches used are specialized components, because they are compatible with routing and switching control pilot signals. The component supports dual supply operation up to $\pm 20\text{V}$, LVTTTL $+3.0\text{V}$ logic compatibility, and immunity from latch-up relating to power supply sequencing. They are manufactured by Maxim with the model number DG417L/DG418L/DG419L. A competitive product from Vishay with the same model number is based on a different process and is incapable of switching voltages less than negative 6 volts.

To allow the micro-controller to sense both positive and negative signals, we used a resistor divider with a series resistor to limit the effect on the signal being measured. These sense resistors were capable of measuring signals between plus and minus 15, which allowed us to read the voltage on the lead-acid battery and the pilot signals. Opting for a symmetrical sense range, the circuit was designed to measure between ± 15 volts.

To protect the input signals from destructive voltage transience, we use two chips. One is designed to protect Ethernet, and the other is designed to protect HDMI. The HDMI chip works like an ESD circuit with diodes between the power and ground rails. The Ethernet chips act more like MOVs but have a lower capacitance.

Appendix B

COMMUNICATION OVER THE CONTROL PILOT

B.1 Control Pilot and Proximity Detection

In the PWM-CP protocol, when an EV is present¹, the EVSE provides a Pulse-Width-Modulation (PWM) signal that indicates the maximum continuous current available. It does not command the vehicle for a specific current; it simply provides an upper bound in amperes. The EVSE measures the PWM voltage that it is generating. The positive side voltage is used to determine the presence and state of a connected electric vehicle, but the negative side should be unloaded².

The vehicle's role in the protocol involves two primary functions. One is to monitor the Plug Proximity signal, which in AC charging modes is handled entirely by the vehicle. The Proximity signal is supplied by the vehicle and loops through the inlet and the cordset plug before being grounded through a resistor³. In other words, the EV provides a positive voltage, but when there is a plug in the inlet it causes a drop in the Proximity voltage, which the vehicle can detect and measure.

¹ Some charging stations leave on their PWM all the time.

² This prevents false positives in vehicle detection. The load is asymmetrical because of the presence of a diode in the circuit, so the resistors only pull down the positive side of the PWM. When ready to charge, the positive portion of the signal from the EVSE is at 6 volts and the negative side is untouched at -12 volts. This would prevent a puddle, water, mud or anything the cable could be dropped into (or touched with fingers) with a resistance equivalent to the ready state.

³ In their generation one AC Charging cable, ITT Cannon brings the Proximity wire back to the EVSE, presumably to allow the EVSE to monitor the state of Prox, although that is not a standard function for AC charging. We have used the presence of this wire to implement several of our own features including cordset cut detection.

The second part of the vehicle's role in the protocol is to signal back the EVSE by loading the positive side of the pilot signal to voltage levels corresponding to states. State A indicates there is no vehicle present and corresponds with an unloaded control pilot. State B indicates to the EVSE that the EV is present, but not currently ready to charge. State C indicates that the car is ready to charge. State D is similar to State C, but additionally requires that EVSE provide air ventilation.

B.2 Replacing the PWM with Digital Data

First let us consider the electrical characteristics of the control pilot signal. Because there is only one communication wire and an AC ground, the communication is inherently single-ended using the existing cord-sets and couplers. Also one of the primary safety functions of the control pilot is the "Verification of Equipment Grounding Continuity" and the "Verification of Vehicle Connection". This means the control pilot must be referenced to the AC ground. This eliminates the possibility of isolated or differential signaling. Maximum system capacitance is derived from three separate components, which include the cordset, the electric vehicle, and the supply equipment. The standards limit the total capacitance to 5500 picofarads or 5.5 nanofarads.

If we change the operation of the control pilot, we still need to be able to detect shorts and opens in the wire. At minimum, it must be able to provide the other functions of the existing control pilot, including indicating supply equipment and electric vehicle readiness and EVSE current capacity. While the PWM frequency is defined at 1 kilohertz, the minimum duty cycle is 5% which is equivalent to a 50 microsecond pulse-width. In a digital system, a 50 microsecond pulse-width implies a bandwidth of 20 Kilobits per second. A digital system utilizing this bandwidth could be seamlessly integrated with existing EMC requirements and existing passive filtering components which may be present in existing control pilot circuits. Also the cost of implementing this circuitry ideally would be as inexpensive or similarly costed as existing PWM circuits. The digital communication needs to be bidirectional as there signals to be sent from both sides. This means a system such as collision detection or

avoidance, bus arbitration, or bus mastering. Because the PWM or equivalent digital replacement is a baseband or non-carrier-modulated signal, it could allow the seamless addition of PLC-type communications if the baseband frequency is low enough by mixing the signals.

B.3 Initial Internal Requirements

1. Sufficiency: The standard should allow us to exchange all the information needed to provide V2G between the EVSE, the EV and Aggregator.
2. Efficiency: The standard should serialize the data efficiently without unnecessary memory, CPU, or bandwidth overhead. For example, the current power being provided can be represented using 2 bytes - transferring several hundred bytes (in the form of XML and HTTP headers and tags) in order to send these two bytes presents an unreasonable amount of overhead that we would like to avoid. HTTP is also often not an ideal protocol for fast dispatch services.
3. Simplicity: The standard should be simple to implement and test. We shouldn't have to implement a whole set of extra required functionality just to exchange the V2G data.

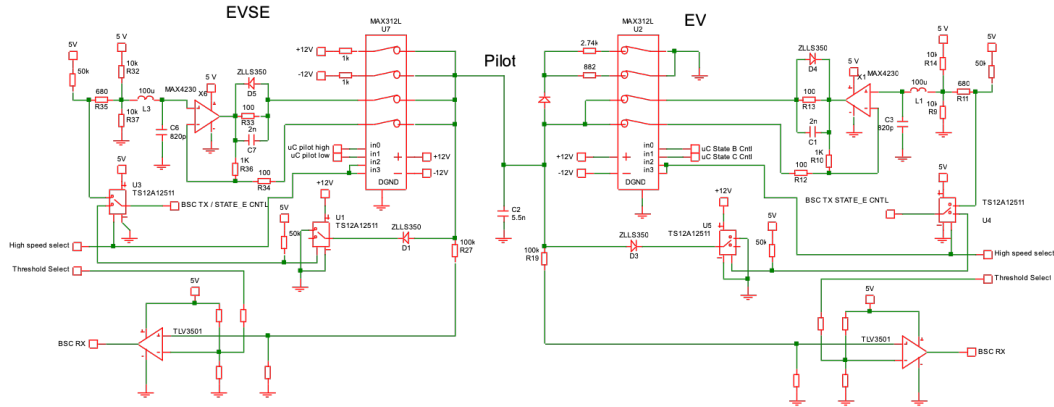
B.4 Negative Side Signaling

Because of its advantages for simplicity and association, we chose to communicate using baseband signaling over the control pilot. Using a single wire and conventional signaling meant that the communication channel would be half-duplex. This left us with a few options for bus arbitration. We decided against a bus-master protocol, and decided to use the CAN-bus protocol. However, because of our physical layer requirements, we needed a custom transceiver for our single-wire CAN. This version used passive pull-ups for the recessive state and open-drain for the dominate state.

B.5 Improved High-speed CANBus Signaling

Later during the standards development process, Lenart Balgård, Andrea Waite, and I designed a circuit that used the positive side of the circuit. It uses active pull up and pull down for symmetrical rise and fall times. The dominate state always wins, allowing for bus arbitration as required by CANBus. This is achieved using a diode

Figure B.1: A near-complete EV and EVSE connected HS-CAN-CP circuit with PWM compatibility. Note the BSC RX and TX terminals connect to the CAN controller which is not shown.



on the output of the transistor to make the impedance lower when trying to pull-down the circuit.

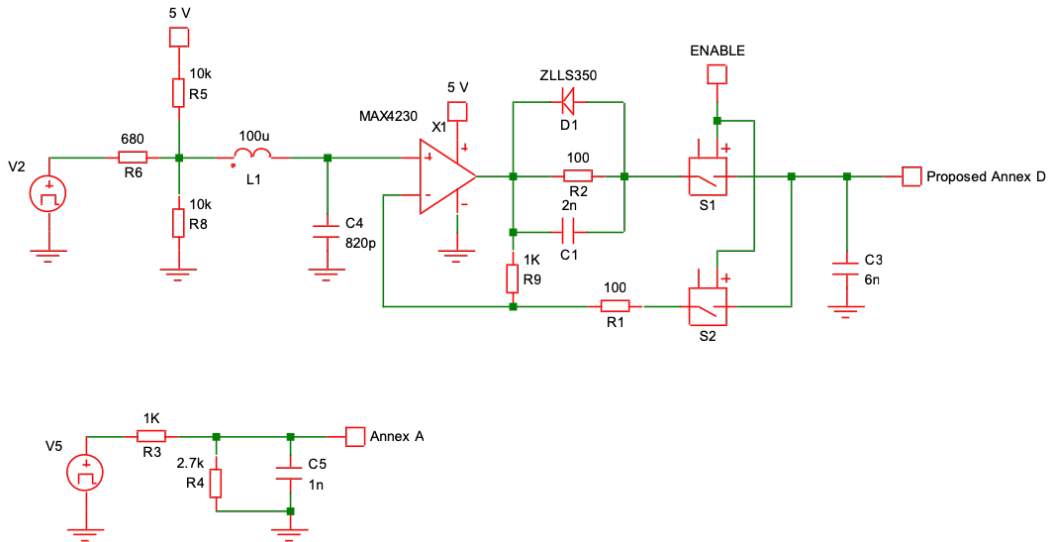
The circuit is designed to handle 300 to 5500 pF, which is the allowed range of capacitance on the Control Pilot circuit. Also we wanted consistent soft edges over the whole capacitance range using an op-amp with wave-shaping to reduce electromagnetic interference. We published a version of this circuit as an optional variant of Annex D in the second committee draft of the IEC 61851-1 edition 3 standard. The circuit showing the vehicle and EVSE side is shown in B.1, while a sub-circuit is shown in B.2, and a simulation of the voltage and current are shown in B.3.

We can take a closer look on how one side preforms of the high speed signaling works vs. the analog pulse-width modulation controls.

B.6 LIN over Control Pilot

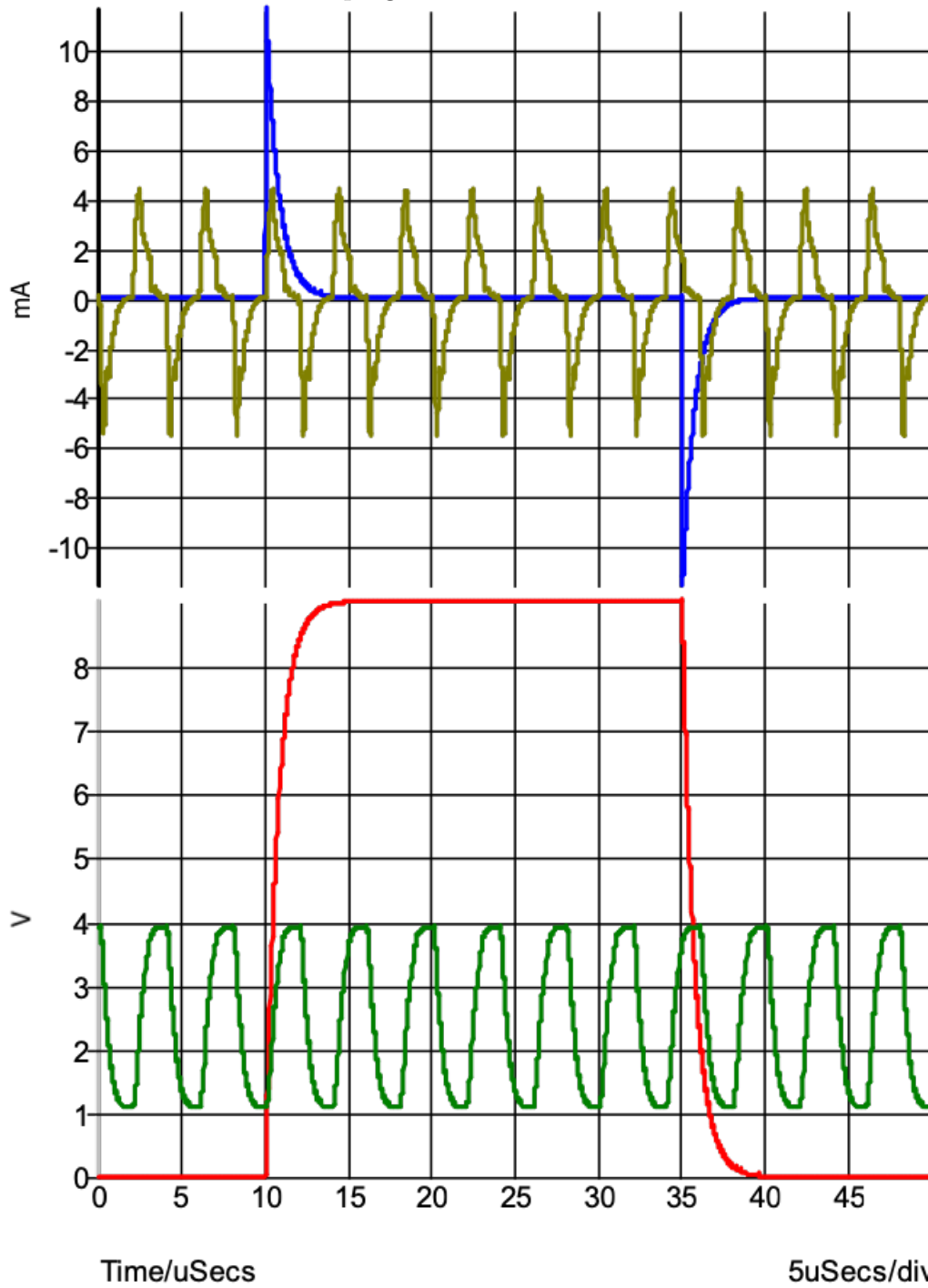
Because of some uncertainty around the use of custom discrete components to build the transceivers for CAN over control pilot, the Annex D task force re-explored using LIN transceivers. The availability of new LIN transceiver parts which have extended supply operation down to 5V meant more compatibility with the non-ventilated voltage states defined in IEC 61851-1 Annex A. One similar technology is known as

Figure B.2: This shows one side of the circuit at the top. The output is named Proposed Annex D and the bottom circuit is PWM and the output is labeled Annex A.



GMCAN and standardized as SAE J2411, Single-wire CAN is used in Tesla's Superchargers.

Figure B.3: The red line shows the PWM for reference, and the blue line shows the large current spikes. The green line shows the high speed CAN and the mustard color shows the current which is lower during the switch because of the wave-shaping.



Appendix C

BI-DIRECTIONAL CHARGER

The bi-directional inverter is a special case of the inverter.

C.1 Rectifier

A rectifier is a device that only allows current to flow one direction. Typically this is used for converting a periodically reversing or alternating current (AC) to one that is in one direction called direct current (DC). The first rectifier was the Fleming oscillation valve, but useful in signal applications these vacuum tubes were not useful for large scale power conversion. Rotary converters were an important tool for high power AC to DC. These were mechanical devices where an AC motor was connected to a DC generator. These were later replaced with mercury arc rectifiers. The first solid state converters were metal plate rectifiers using copper-oxide or steel plated with selenium. Later germanium and silicon devices would prove efficient enough to replace previous methods.

C.2 Inverter

According to an IEEE industry applications publication from early 1996 [18], "David Prince probably coined the term inverter" in his 1925 publication titled "The Inverter." The concept of using "grid control" [find alternative definition] with phase retard to modulate AC power occurred about 4 years earlier by Moritz Schenkel [21]. Prince, apparently, took Anderson's term "inverted rectification" and synthesized a new word "inverter". The concept is to refer to an opposite mode of operation from the rectifier. The term depends on the fact that the rectifier had existed since the late 1800s, one example of which was rotary converters which were used until they were

replaced with devices based on germanium diodes in the early 1950s. Prince elaborated that an inverter would convert direct current into single or polyphasic alternating current.

The IEEE defines inverter (electric power): "a machine, device, or system that changes direct-current power to alternating-current power." One early application of small-scale inverters was needed to power inventions like GE's Monitor top refrigerator in 1924. Since the device used an AC compressor and some major US cities still used DC power, they required inverters to operate. The introduction of the thyristor (also called the silicon controlled rectifier or SCR) was invented by GE in 1957 and was an important advancement in inverter technology.

While electric vehicles have existed since the late 1800s, the early 1990s proved an important time period for the advancement of vehicles with onboard inverters. Two big advancements by Wally E. Rippel in US Patent Numbers 4,920,475[19] and 5,099,186[20] and Alan G. Coconni in Patent Number 5,341,075[8] introduced the invention of a combined traction inverter and battery charger apparatus. This means a single set of electronics is used to charge the battery from the AC grid and drive the three-phase electric motor for propulsion. Before this, electric vehicles relied either on stationary off-board inverters, which often included low-frequency transformers and other electrical equipment too heavy to be installed on a vehicle. Other vehicles used on-board charging systems, which were separate from the traction electronics, but ultimately reduced in power level for cost/ size/ weight reasons. Coconni notes that many of these on-board chargers were implemented using SCRs or triacs, which suffer from poor power factors and are generally not suited for high power applications on-board vehicles.

Rippel's second patent improves on the design by using the motor windings to eliminate the input rectifier in the charge mode. One disadvantage of the second Rippel design is the high current on the ground wire, which represents a potential safety hazard and issues with AC sources powered with ground fault interrupters. The Coconni design employs "essentially conventional" poly-phase pulse with modulated inverter.

The unconventional aspect is that the motor windings can be selectively decoupled and used as inductive circuit elements in a boost switching regulator. In addition, shielding is employed to reduce common-mode currents, making the device compatible with circuits with ground fault interrupters. In the background of the Coconni patent, there is one sentence that is crucial in the history of vehicles with inverters which reads, "Furthermore, due to the bi-directional nature of the inverter switches, sinusoidal, regulated AC power can be developed from the battery and provided as an output at the recharge port."

By virtue of its functionality, the inverter controls the power flows through the battery. For on-board charging, the inverter and battery are part of the same OEM system. The control dependencies between inverter and battery should be designed so that, over time, such power flows meet the following requirements:

- Requirement 1 (respect of battery safety limits) is naturally ensured by the OEM. However, these standards specify only the maximum safe limits, and do not necessarily provide the information needed for
- Requirement 2: optimum efficiency. For instance, when providing grid services like frequency regulation, the cost in battery wear of cycling the battery at unusually high battery temperatures may be higher than the cost at normal battery temperatures, and so grid services might be avoided at that time unless the benefit of such service is very high. Battery temperature data resides in the vehicle, and that information would need to be part of the control system in order to execute an optimized system. Temperature is just one example of a parameter that could be used that only the vehicle knows.
- Requirement 3 (state-of-charge management / schedule) must be covered by the architecture of the overall V2G control system, including driver, vehicle, charging station, and aggregator. For the UD architecture, the vehicle identifies itself and constantly provides its state of charge to the VSL (and not to the EVSE or the market aggregator). The VSL uses this in conjunction with a driver's schedule to calculate the type of services it is willing to provide and the time at which it is willing to provide them. The driving schedule comes from either the cloud scheduling system for this project or the vehicle telematics and the trips may be entered in through an application.

Appendix D

AC OR DC

Virtually all electric cars use 3-phase AC motors, and therefore require a motor inverter to drive the motor from the battery. In order to handle the acceleration and speed needed for highway driving, substantially sized power electronics are needed.

Some people argue for leaving all high-speed charging for DC, and also using DC buses for discharging. This argument stems from the cost of increasing the power capacity of separate on-board chargers and inverters.

However, integrating the charger into the main power electronics would eliminate this extra cost. For adding V2G in the system traditional thought requires a third piece of power electronics to the electric vehicle. This would mean that we would have three different power electronics units for AC to DC conversion, either on-board or external to the vehicle.

Once you have a charger integrated into the primary power electronics, the next step turns the motor inverter into a grid-tied inverter. Integrated AC charging and discharging eliminates all external AC to DC conversion. AC/Propulsion has demonstrated such a drive-train since 2001. It uses transistors configured via contactors for all power electronics functions.

Medium power integrated charging and discharging within the vehicle systems generally use a non-galvanic isolation because of the bulk and weight of adding a large transformer in a vehicle. For the safety of electric vehicle system using integrated charging and discharging follow the safety regulations developed for transformer-less PV inverters.

Many of the techniques required to create power electronics require advanced DSP motor control systems which exist in similar forms for the primary drive motor

for the AC motor. We can either duplicate and reuse the silicon in these systems or reuse them.

Many considering V2G with today's vehicles see the quickest path forward as using separate curbside power electronics for DC charging/discharging. Directly interfacing with the DC bus and charging the battery in cooperation with the vehicle's BMS is considered a cheap way to allow very fast charging. However the model for V2G is that the cars will spend most of their time parked, plugged in. Generally, DC charging systems with high capacity are meant for short term charging, somewhere less than 30 minutes of charging and then the vehicle leaves. In order to have the scenario in which most parked electric vehicles can be connected to the grid, one needs to decrease the amount of infrastructure cost associated with connecting these cars to the grid.

If the additional components cost of integrating charging and discharging capabilities into existing primary drivetrain is lower than the cost of implementing that capability as an external component. For our projects, we favored an on-board bidirectional system, due to lower potential total system cost and more hours of availability since the vehicle can be plugged into lower cost AC EVSE infrastructure. But an off-board also is viable and has advantages for an OEM with an existing DC inlet. It minimizes the engineering design effort by the OEM and moves the responsibility of grid interconnection to the off-board device.

Below we consider two types of on-board chargers vs. integrated drive-train chargers and then consider off-board chargers:

Integrated chargers use the vehicle power electronics for charging and optionally discharging. This is possible because the vehicle contains power electronics for the AC motor including drive inverter and regenerative braking which is a high-power bidirectional system. Experience by Tier 1 suppliers report dramatically lower cost for high power AC chargers. The Renault Zoe supplier Continental has said adding charging functions to the parts already used for propulsion adds only 200 euros in parts. This charger operates at charging rates up to 42 kW. Similarly, AC Propulsion reports that starting from the drive electronics, adding bidirectional charging added

about \$400. No separate on-board charger, and certainly no off-board charger, can be produced at such low cost; such systems are also lower weight and smaller packaging. There are design trade-offs that must be carefully analyzed.

We worked with OEMs and supply equipment manufacturers for AC or DC solutions, but the costs and benefits should be understood for any approach to be viable in the long run. We would be interested in integrating the VSL for either case. Ultimately the viability of off-board vs. on-board comes down to cost and benefit.

For further reading on the topic of bidirectional AC chargers and V2G is discussed in this thesis by Joachim Johansen from DTU, Denmark who spend several semesters here at UDel. He now works for Tesla. <http://udel.edu/jsj/JSJ-EV-AC-Fast-Charging-Thesis.pdf>

Two OEM suppliers told us that, for them, modifying their on-board charger to be bidirectional was a software-only modification. It required a rewrite of their DSP that controls the switching devices to allow for two-way flow modes. This is not the case for all on-board chargers. For example, some may need to modify their IGBT switching power configuration layout to allow for bidirectional flow. Other may need to add filters to reduce harmonics.

We generally advocate home and work charging to maximize the benefit to the customer for both V2G revenue and for maximizing potential vehicle range. For an off-board V2G in this use-case you would need two bidirectional DC chargers. The DC fast charger use case for en-route charging is quite a bit different than the V2G use case. With fast charging you generally want to minimize the time spent plugged in and waiting en route, but with V2G you want to maximize the time plugged in to maximum revenue.

A low-power and low-cost DC off-board bidirectional charger, if one becomes available, could be an option for an OEM which already has a DC interface allowing two-way flow. There would be two advantages to this: no power design on the vehicle would be required, and the off-board charger would use existing standards for electrical equipment (e.g. UL or CE) for back-feeding. Also, fault analysis on the vehicle side is

simplified. This may make it interesting for a demonstration project not intended for a production vehicle, as permitting could be faster and the higher cost to the customer is not a consideration.

Standards for interconnecting AC vehicles are currently being developed in the SAE. This would resolve the problem of certification of the on-board charger. Several OEMs with prototype units or intention of producing on-board bidirectional chargers. When considering costs, the cost of public charging should not be ignored. An AC charging connection for an on-board charger (EVSE) is much lower cost and much less maintenance than DC charging equipment.