Jerry Brown
Governor

SEAMLESS MECHANIZED CHARGING INTERFACE FOR EV/PHEV

INDEPENDENT ASSESSMENT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program
Energy Innovations Small Grants Program

March 2013
CEC-500-98-014

Prepared By:
San Diego State University Research Foundation
Rob Queen
5250 Campanile Drive
San Diego, CA, 92182-1858
Contract No. 500-98-014
Grant # 10-05TE

Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Raquel Kravitz
Program Manager
Energy Innovations Small Grant Program

Mike Gravely
Manager
Energy Systems Research Office

Laurie ten Hope
Deputy Director
Energy Research and Development Division

Robert Oglesby
Executive Director

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Research Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Attachments
    - Attachment A: Final Report (under separate cover)
    - Attachment B: Grantee Comments to Independent Assessment (grantee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

With the proliferation of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV), consumers are increasingly experiencing the inconvenience of daily charging. This is particularly true for home garage locations where more than 90 percent of the charging events occur, and it is also where the chore of charging is a daily occurrence.

The EV industry has already recognized the need for a hands free charging technology to provide a more positive user experience. Under this EISG grant the research team developed the first practical conductive hands free charging technology. This is a conductive system as opposed to an inductive technology that industry is presently trying to develop. Inductive chargers waste 10—25 percent energy into heat and also generate high levels of magnetic fields hazardous to pets, pacemakers, and structural members of a garage.

The CrossBar technology developed in this project has a pair of bars with conductor geometries such that their cross point located anywhere on the bars will establish multiple conductive paths needed for charging. It trades off the mechanical complexity for added power electronics. The first generation of the technology developed here is rated for 240 V AC and 32 A. It tolerates up to 14″ × 16″ of parking misalignment and up to ± 10° of yaw misalignment. The system exceeds the contact quality as well as robustness requirements. Being conductive, it transfers the charging power with better than 99 percent efficiency. High efficiency and elimination of magnetic fields permit this technology to be scalable to high power levels necessary for quick charging.

Keywords: Hands free, charging, conductive, electric vehicle(s), EV, PHEV, quick charging

Introduction

The full realization of petroleum displacement and reduced air quality emissions resulting from substantial penetration of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) into the California vehicle marketplace will be highly influenced by consumer behavior and habits. Charging requirements for such vehicles are one principal impediment. A reliable and seamless charging system developed under this EISG grant could be a key to successful deployment of EVs and PHEVs. In a survey conducted by the research team, almost half of the consumers otherwise not interested in EVs indicated that hands free convenience would change their minds about EVs in a favorable direction.

Two important facts make the EV/PHEV refueling process less convenient for consumers:

1. Most cost effective EV/PHEVs need ten times more frequent refueling compared to their fossil fuel counterparts. Specifically, the average commute distance in California is 22 miles each way; average fuel efficiency is 25 miles per gallon. An average gas tank of 16.5 gallons will last for 9.3 commute days. In contrast, a full charge will last between 1 and 1.8 days. Chevy Volt has an all electric range of about 40 miles, and Nissan Leaf has an average range of 80 miles.
2. Charging cycles typically last 4 to 8 hours (Chevy Volt four hours @ 240 VAC, 15 A and Nissan Leaf eight hours @ 240 VAC, 15 A) as opposed to less than 10 minutes refueling for a typical gasoline fueled passenger car.

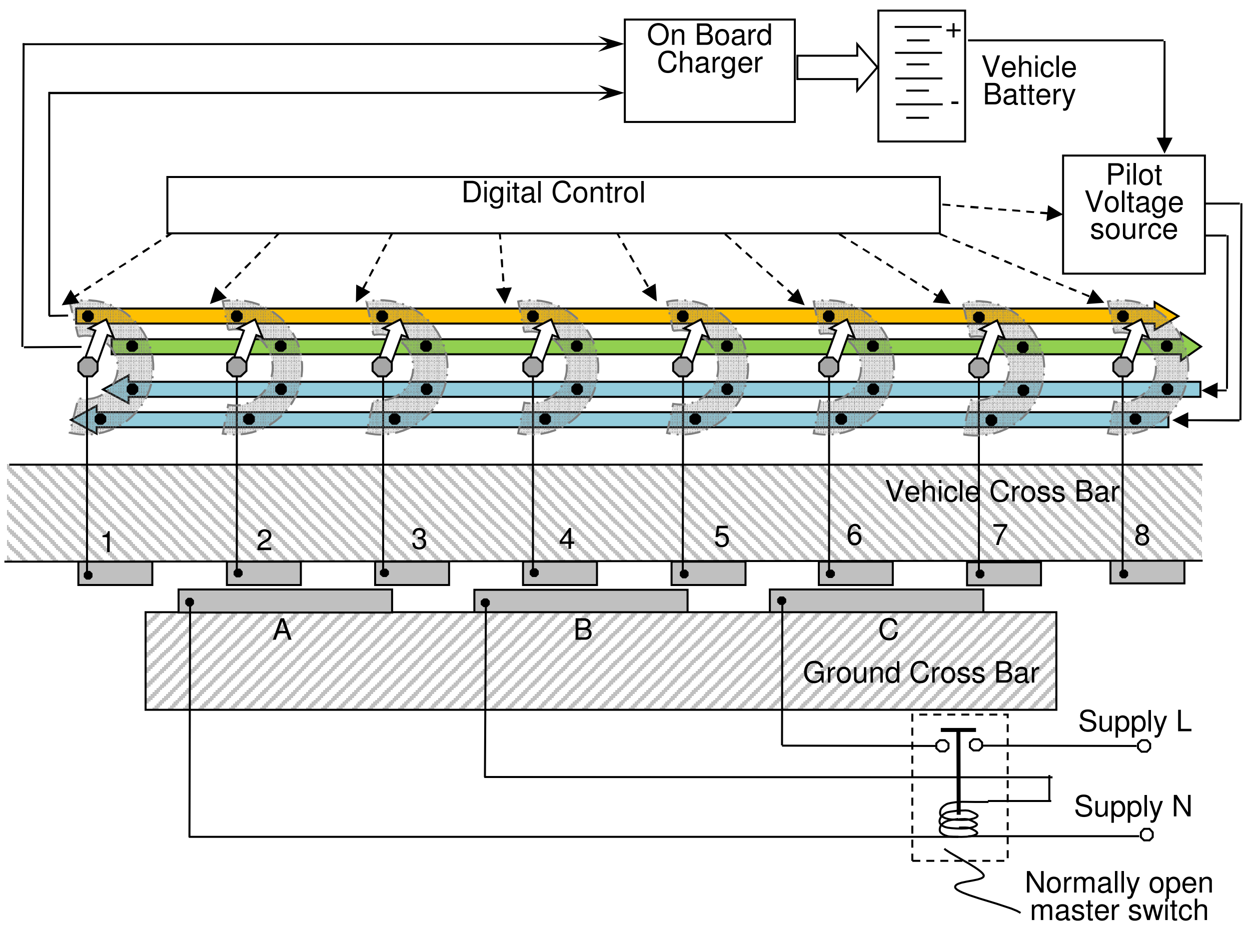
Unless this inconvenience is addressed, the missed charge cycles will end up costing California commuters gasoline for the next commute day. Thus the cost of missed charge cycles can be calculated as follows: average carbon dioxide (CO_2) emission per gallon of gasoline is 19.4 lb. Combining this with average commute distance in California and average fuel efficiency, one can calculate the typical carbon footprint of a missed charge cycle to be 34 lb of CO_2 for an average commute. With about 12.8 million commuters in California, if each commuter forgot to charge once per month, environmental costs would quickly add up to 2.4 megatons of CO_2 per year and 12 million barrels of oil.

In addition, the technology developed in this project would produce electricity savings. The average daily electricity need of an EV is 24 kWh. When compared to competing inductive technology, which can be up to 75 percent efficient for normal parking accuracies, hands free charging technology developed under this grant would further save 8 kWh energy per charge cycle or 2.9 MWh of saving per year per charger.

With the advent of automatic and seamless charging technology developed under this EISG grant, there would be negligible dependence on consumer behavior modification for successful adoption and maximum utilization of electric vehicles. This would allow California ratepayers to reap the benefits of a larger pool of grid connected PHEVs and EVs while saving the environmental costs of missed charge cycles.

This charging connection development brings together innovations in several technical domains such as geometry, materials, surface interactions, surface topology, power electronics, electrical interlock, software, radio frequency (RF) communication, and mechanical packaging. Figure 1 displays the overall concept along with electrical connections, interlock, and geometry definition.

Figure 1: Overall Concept Including Electrical Connections, Interlock, and Geometry Definition



The charging connection developed in this EISG project is the first conductive technology to automatically connect EVs to the charging infrastructure. In its basic form the technology comprises two bars, each with a series of independent electrical contacts. One of the bars is placed on an actuating mechanism on the ground and is moved toward the second bar, which is mounted on the underbelly of the vehicle. Depending on the parked position of the vehicle with respect to the ground, an arbitrary pair of regions from each of the bars overlaps. At that point a microprocessor, along with appropriate power switches, scans all contacts and identifies the mating pairs. Only those contacts in a circuit between the power source and battery are connected, with all other contacts being electrically excluded. Mechanical and sensing complexity of searching and precisely locating mating contactors is eliminated, and the same functionality is encapsulated in power electronics, making the technology robust and reliable.

Objectives

The goal in this project was to determine the feasibility of a practical hands free charging technology producing a high quality conductive connection between the parking stall and an electric vehicle parked within the normal parking ability of a typical driver. In its basic form, the technology comprises two bars, each with a series of independent electrical contacts. One of the bars is placed on an actuating mechanism on the ground and is moved towards the second bar, which is mounted on the underbelly of the vehicle. Depending on the parked position of the vehicle with respect to the ground, an arbitrary pair of regions from each of the bars overlaps. At that point a microprocessor, along with appropriate power switches, scans all contacts, identifies the mating pairs, and connects those contacts in a circuit between the power source and battery, with all other contacts electrically excluded.

This is a conductive system as opposed to the inductive technology that industry is presently trying to develop. Inductive chargers waste 10—25 percent energy into heat and also generate high levels of magnetic fields hazardous to pets, pacemakers, and structural members of garages.

The researchers established the following project objectives:

1. Design a hands free charging system for EVs.
2. Realize a charging system that demonstrates the ability to connect a vehicle to the grid within ±20 cm and ±10° misalignment.
3. Develop a test stand and demonstrate that it is capable of positioning a vehicle connector within at least ±20 cm and ±10° misalignment.
4. Demonstrate that the charging system can perform repeated operation for at least 1000 cycles of operations with random misalignment within ±20 cm of lateral and longitudinal directions, ±10° of yaw angle and contact resistance no greater and 100 mΩ.
5. Confirm from project findings that the technology can be mass produced for $100/device manufacturing cost.
6. Confirm from project findings that seamless charging will save environmental costs within 10 missed charging cycles per year.
7. Confirm from the project findings that seamless charging technology can save two million tons of CO_2/year for California.
8. Conduct component level tests on the mating contactors and document the effect of contact force on contact resistance for different contact geometries and the effect of exposure to ASTM-B117 test protocol on the contact resistance.

Outcomes

1. The researchers successfully designed a conductive hands free charging system for EVs.
2. The researchers demonstrated the charging system could connect a vehicle to the grid within ±20 cm and ±10° misalignment.
3. The research team designed and built a test stand comprising a rectangular platform with wheels at each corner. The test stand was capable of being positioned at an arbitrary lateral/ longitudinal/angular offset with respect to the ground side mechanism, thus achieving Objective 3 while being able to measure its position with respect to the ground side mechanism.
4. The research team was able to demonstrate all except one property during operation. See Table 1. A slightly shorter range in the longitudinal direction was the consequence of some early stage design choices. Since this was not due to an inherent limitation of the tested technology, it can be resolved in the next iteration of the design after verifying the actual range requirements.

Table 1: Outcome Summary of Operational Tests

Actual	Target	Obj. Met
Lateral range: ± 20.32cm	± 20cm	yes
Longitudinal range: ± 17.8cm	± 20 cm	no
Yaw range: ±10°	±10°	yes
Reliability: 1000cycles	1000cycles	yes
Contact Quality: 10 ~ 24 mΩ	< 100 mΩ	yes

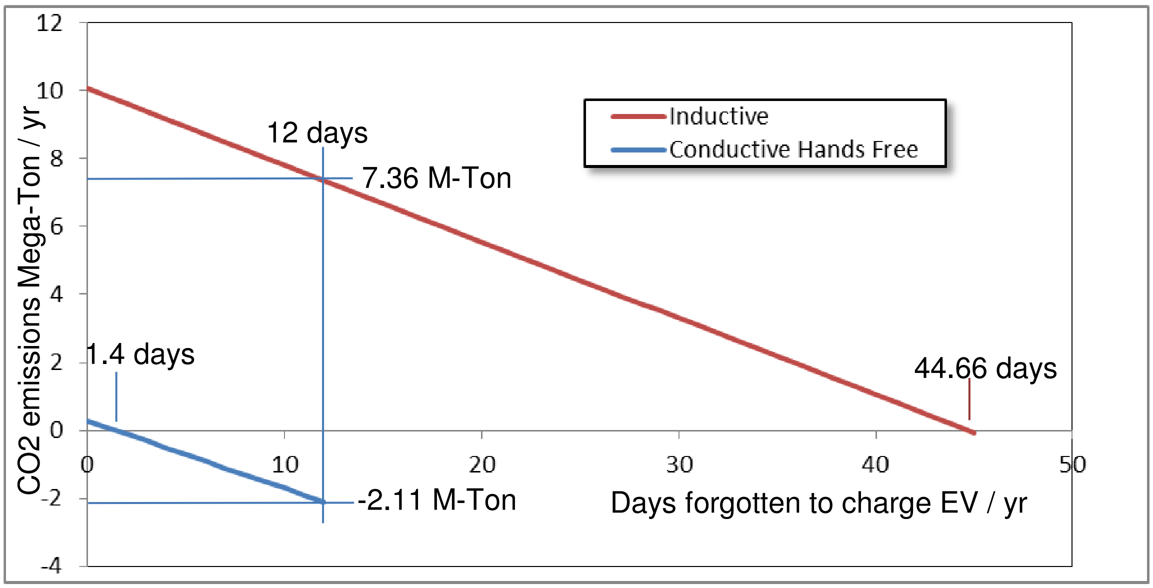
5. The cost objective was not met. Instead of being able to demonstrate that the technology can be mass produced for $100/device, the production estimate was approximately $478. In the short term $100/device target objective is difficult to meet. However the cost of a hands free changing device is about the same as available manual chargers. Due to the key simplifications enabled by the proposed connection technology, the incremental cost of a hands free device is still within an acceptable price point range as noted in consumer surveys. The primary findings of the survey are:

   - Most of consumers consider some form of hands free charging to be beneficial. Only 1.3 percent of the surveyed said they would be happy with manual charging. About 32 percent indicated they would want to have hands free convenience.
   - Most of the consumers (about 81 percent) were willing to attach a value ranging between $200 and $1000 for this convenience. A small percentage (9 percent) indicated willingness to pay more than $1000.

- About half of the individuals (45 percent) otherwise not interested in EVs said they would change their minds if hands free convenience were available.

6. The research confirmed that seamless charging would save environmental costs within 10 missed charging cycles per year. As can be seen in the figure below, even when a consumer forgets to charge 1.4 days (rounded to 2 days per year), the technology developed in this project would benefit the environment.

Figure 1: Sensitivity Analysis for LCA with Respect to Consumer Behavior



7. The research team met this objective by demonstrating that the environmental savings would be greater than two million tons of CO_2/year for California.
8. This objective was met through component level tests on the mating contactors and documentation of the effect of contact force on contact resistance for different contact geometries and the effect of exposure to ASTM-B117 test protocol on the contact resistance.

Conclusions

Based on the work conducted in this project, the conclusions are:

1. The project team developed a conductive hands free charging technology for EVs and PHEVs.
2. The researchers met this Objective.
3. The researchers fabricated a test stand able to position the vehicle side at an arbitrary but measurable position with respect to the ground side, thus meeting this Objective.

4. The charger was able to establish a high quality (low contact resistance) charging connection across a wide range of parking misalignments without involving robotic search or intrusive vehicle guides.

   - The charging system demonstrated a very low contact resistance (10 mΩ— 4 mΩ) across 14″ (longitudinal) × 16″ (lateral) parking misalignments.
   - The charging system demonstrated acceptance of at least ±10° of yaw misalignment, while still delivering high quality contact (10 mΩ—24 mΩ).
   - The system showed no sign of degradation in contact resistance or in physical condition after 1000 cycles of operation. Although testing was stopped after 1000 cycles, the system reliability was estimated to be substantially more than 1000 cycles.

5. The mechanical complexity of the entire system was moderate and the entire system can be manufactured for under $500. While this did not meet program objectives, survey data compiled under Objective 6 indicate it can be considered in line with the consumer acceptance for the usefulness of the product.
6. The research confirmed that seamless charging will save environmental costs within 10 missed charging cycles per year.
7. The system delivers the hands free convenience without any environmental penalty. By eliminating the missed charge cycles, the system can save California up to 2 megatons of CO_2 emissions and 12 million barrels of oil per year.
8. Component level tests have proved that the system is robust against abuses and can deliver very high quality of connection. Contact resistance near 1.5 mΩ was achieved even after exposure to ASTM-B117 (salt and fog) test protocol.

Several key engineering innovations resulted in delivering a reliable charging connection to an arbitrarily parked EV. Even for well aligned connectors and switchgear, it is typically a challenge to deliver contact resistance consistently in the low mΩ range. This is frequently due to sub miniaturized contacts in such devices, where the problem of maintaining consistent operating conditions such as pressure and sliding across a large array of contactors is difficult. The design developed in this project was specifically targeted to address these technical challenges by taking advantage of larger geometries and having multiple redundant conduction paths, at least one of which is optimal. The researchers proved feasibility.

Recommendations

The next step for this technology is to conduct testing in real life environments. The testing should be based on and use industry standards. Such tests can be categorized into three groups: environmental simulation testing such as high-low temperature, icing-freezing, salt and fog, rain, altitude, sand and dust tests; dynamics and vibration testing such as random, sine, shock, seismic, acceleration testing; and electrical testing. Following completion of the testing, a final redesign should be compatible with large volume production processes. As a process, the steps would be:

1. Undergo in-vehicle reliability and functionality tests. The tests should include: environmental simulation testing, dynamics and vibration testing, and electrical testing.
2. Gather data with actual use cases.
3. Go through regulatory certification testing using protocols developed by Underwriters Laboratory (UL) and others.
4. Conduct another round of redesign to include all the changes and improvements resulting from in-vehicle testing, certification testing, and use case data, and modify the design to make use of mass production processes.

While the research team indicated that it has discussed the technology with major automakers, a partnership(s) should also be garnered during this time.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased the use of alternative fuels

The primary benefit to the ratepayer from this research emanates from reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use.

Apart from convenience to drivers, a conservative estimate of environmental savings offered by reliable hands free charging for California is estimated to be 2.4 megatons of CO_2 and 12 million barrels of oil per year. When compared to its competition, this technology would further save up to 2.2 MWh of electricity every year for every charger. In a recent survey conducted by the project team, almost half of the individuals who were otherwise not interested in EVs said they would change their minds if a hands free charger were available. A hands free charger without environmental penalties would promote deeper EV penetration. This would allow California ratepayers to reap the benefits of a larger pool of grid connected PHEVs and EVs.

Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Green Dot does not have financial and market strength to undertake commercialization. The researchers identified Tier 1 auto suppliers (e.g., Delphi, Siemens, and Johnson Controls) as potential marketing partners.

Engineering/Technical

The researchers estimated that they would need about one year and $0.5 million to complete engineering work and produce a prototype. Additional funds would be needed for tooling once commercialization commenced.

Legal/Contractual

The research team has one patent, US #12168137. This is a utility generic technology patent describing the overall concept of CrossBar. The team also has two other patent applications describing design details that are in different stages of prosecution, US #13413646 and #13413647.

Environmental, Safety, Risk Assessments/ Quality Plans

These plans must be addressed during the completion of the engineering work. Appropriate codes and standards must be addressed.

Production Readiness/Commercialization

The researchers plan to work with an electric vehicle manufacturer to begin the commercialization process.

Attachment A: Final Report (under separate cover)

Attachment B: Grantee Comments to Independent Assessment (none submitted)

Attachment A – Grantee Report

Seamless Mechanized Charging Interface for Ev/Phev

Prepared By:

Satyajit Patwardhan
Green Dot Transportation Inc.
670 Navajo Way, Fremont, Ca 94539
Phone: (510) 364-8280
Email: satyajit@engineeralum.berkeley.edu

Grant # 10-05TE
Contract No. 500-98-014

Prepared For:
San Diego State
University Research Foundation
5250 Campanile Drive
San Diego, CA, 92182-1858