Comprehensive Assessment of On-and Off-Board V2G Technology Performance on Battery and the Grid

ELECTRIC POWER RESEARCH INSTITUTE

Project ID ELT187

2020 US Department of Energy Vehicle Technologies Office Annual Merit Review

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Outline

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- Milestones
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- Critical Assumptions/Issues

Overview

Timeline

- Start – November 2016
- Finish – June 2020*

Percent complete: 85%

Barriers

- Insufficient Data on DER Applications
- Value of V2G integration as DER asset
- On and Off-Vehicle Hardware
- Cost, performance, communications, monitoring, and control
- Standards, interoperability

Budget

- Govt Share: $1,547,678
- Cost Share : $1,238,600
- Total Program: $2,786,278

Funding for FY 2017: $860,679

Funding for FY 2018: $631,826

Partners

- Lead: EPRI
- Partners: Flex Power Control, FCA, Kitu,
- Collaborations: NREL and ORNL, SAE

Focus on Open Standards Implementation of Vehicle-to-Grid as a BTM DER Technology

Relevance

Objective

- Develop and demonstrate power electronics and energy management controls system enabling vehicle-to-grid (V2G) bi-directional power flow (V2G) integrated with solar and stationary energy distributed resources
- ***Smart Power Integrated Node (SPIN)*** – single multi-functional modular unit integrating solar, stationary energy storage, and V2G power electronics with the localized DER Management System.

TI Goals

- *National Security* – Enable maximum local DER use behind the meter
- *Economic Growth* – Create a path for value from DER and V2G dispatchability enabled by SPIN to be available as incentives to EV owners.
- *Affordability to Consumers* – Reduce part and installation costs through system integration
- *Reliability/Resiliency* – Provide standby power to the premise in case of an outage, through synergistic application of Solar, Storage and EV

Impact

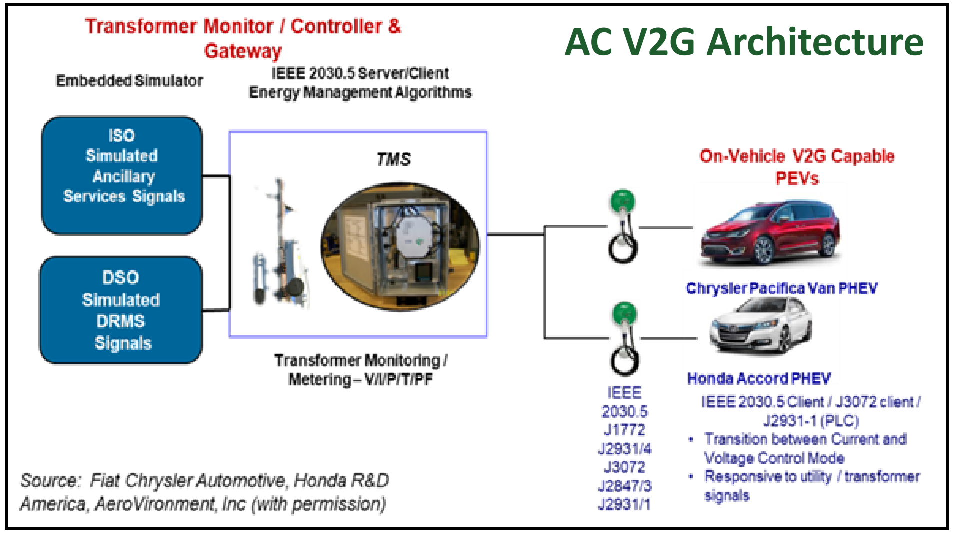
- Open standards implementation – SAE J1772, IEEE 2030.5, J2847/2, J2847/3, J3072, J2931/1, J2931/4
- Viability of V2G as DER resource and cost/benefit to consumer and utilities
- Battery durability impacts from V2G

V2G Technology Viability, Value and Battery Impacts – Key Enablers of a DER Ecosystem

Approach: Open Standards-Based V2G

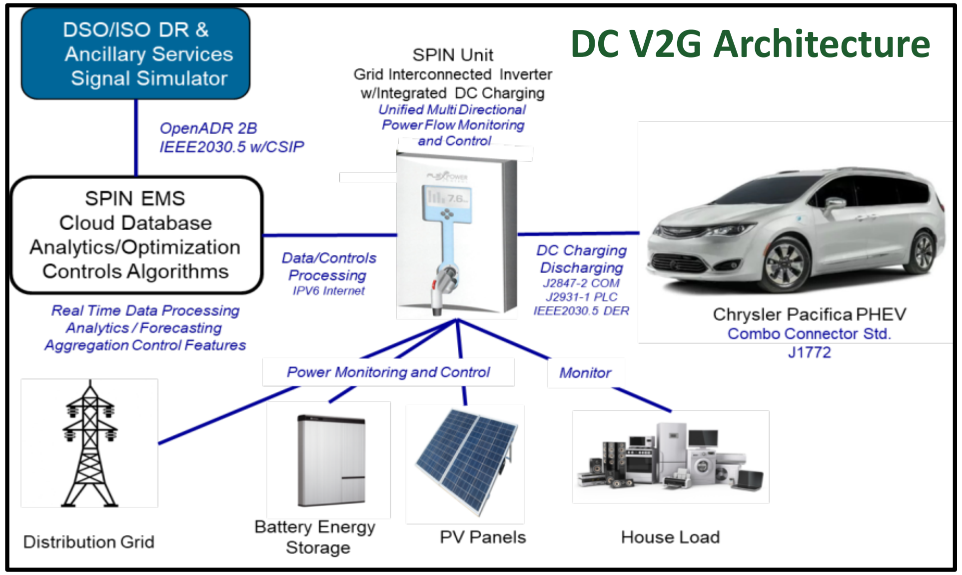
1. On-Vehicle AC V2G

- Incorporates ***Transformer monitoring and controls*** to manage multiple connected V2G capable PHEVs
- Transformer Management System w/IEEE2030.5
- L2 EVSE Bridge w/J3072 Authentication S/W
- Chrysler Pacifica Van PHEV and Honda Accord PHEV w/IEEE2020.5 /J3072 S/W



2. Off-Vehicle DC V2G

- ***Smart Power Integrated Node*** **(SPIN)** for integrating off-board V2G with PV and storage
- J1772 CCS DC Charging w/J2847-2/J2847-3/ IEEE2030.5 Control
- Chrysler Pacifica PHEV with J1772 CCS, J2847-2/J847-3/IEEE2030.5 implementation
- SPIN Integrated DER energy management system
- Monitoring and controls through cloud data analytics and optimization algorithms



Source: EVSE Images – AeroVironment, Inc, Transformer Monitoring System (TMS): EPRI Technology, Battery Storage LG Chem, PHEV Images – Fiat Chrysler Automobiles and Honda R&D America

On-Vehicle: Distribution Services and Value; Off-Vehicle: BTM DER Integration, Storage Test

BP3 Milestones

Budget Period 3
Apr 2019 – Jun 2020

Description	Type	Planned Task Detail
Complete OEM Vehicle / SPIN DC V2G Communications Implementation and Verification	Oct 2019	• Development, implementation and testing of SPIN DC Communications Control Module (CCM): DC V2G based on SAE standards (J2847/3, DIN Spec harmonized, IEEE2030.5) • Interoperability DSO Server/SPIN/Vehicle (MY 2021 FIAT 500 EV) communications
Complete V2G Lab Demonstration	Dec 2019	Perform Vehicle/SPIN integrated demonstration. (Delayed)
Complete Demonstration Report	Feb 2020	Report will be generated covering the demonstration and data from characterization and use case functional testing.. (Delayed)
Complete Battery Pack Durability Test Report	Jun 2020	Assessment and evaluation of impact from 6 month V2G cycle operations. Pack impedance/capacity will be evaluated before and after the testing. (Delayed)

BP3: System Integration and Battery Evaluation

Project Accomplishments/Progress

On-Vehicle V2G Development

The work resulted in four publications:

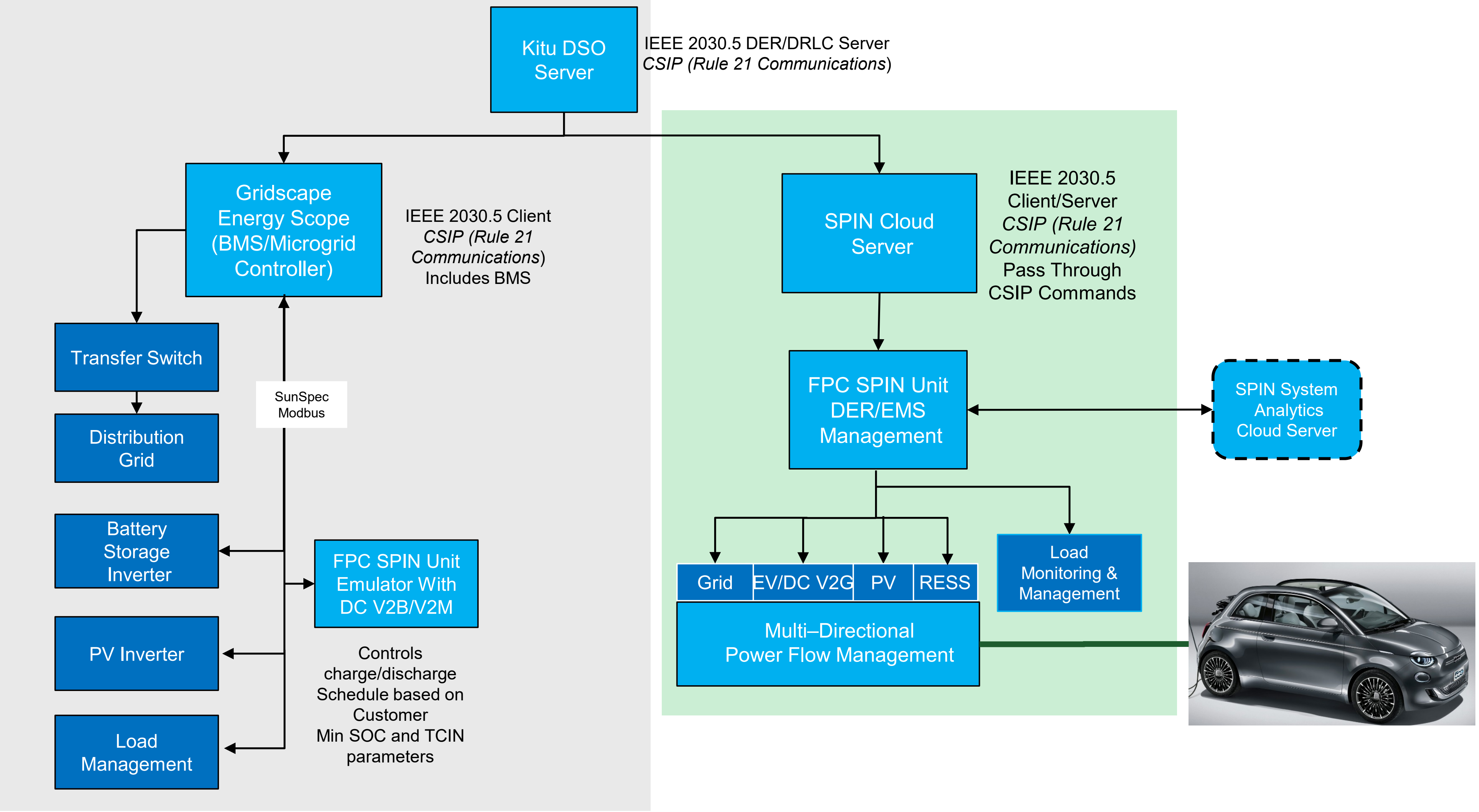
- 'Open Standards-Based V2G: Technology Development', EPRI:3002014770, 2018
- 'Open Standards-Based V2G: Integrated Resource Planning Considerations', EPRI:3002014801, 2018
- 'Open Standards-Based V2G: Value Assessment', EPRI:3002014771, 2019
- Chhaya, S., et al, 'Distribution System Constrained Vehicle-to-Grid Services for Improved Grid Stability and Reliability', California Energy Commission, CEC-500-2019-027, 2019

Off-Vehicle V2G Development

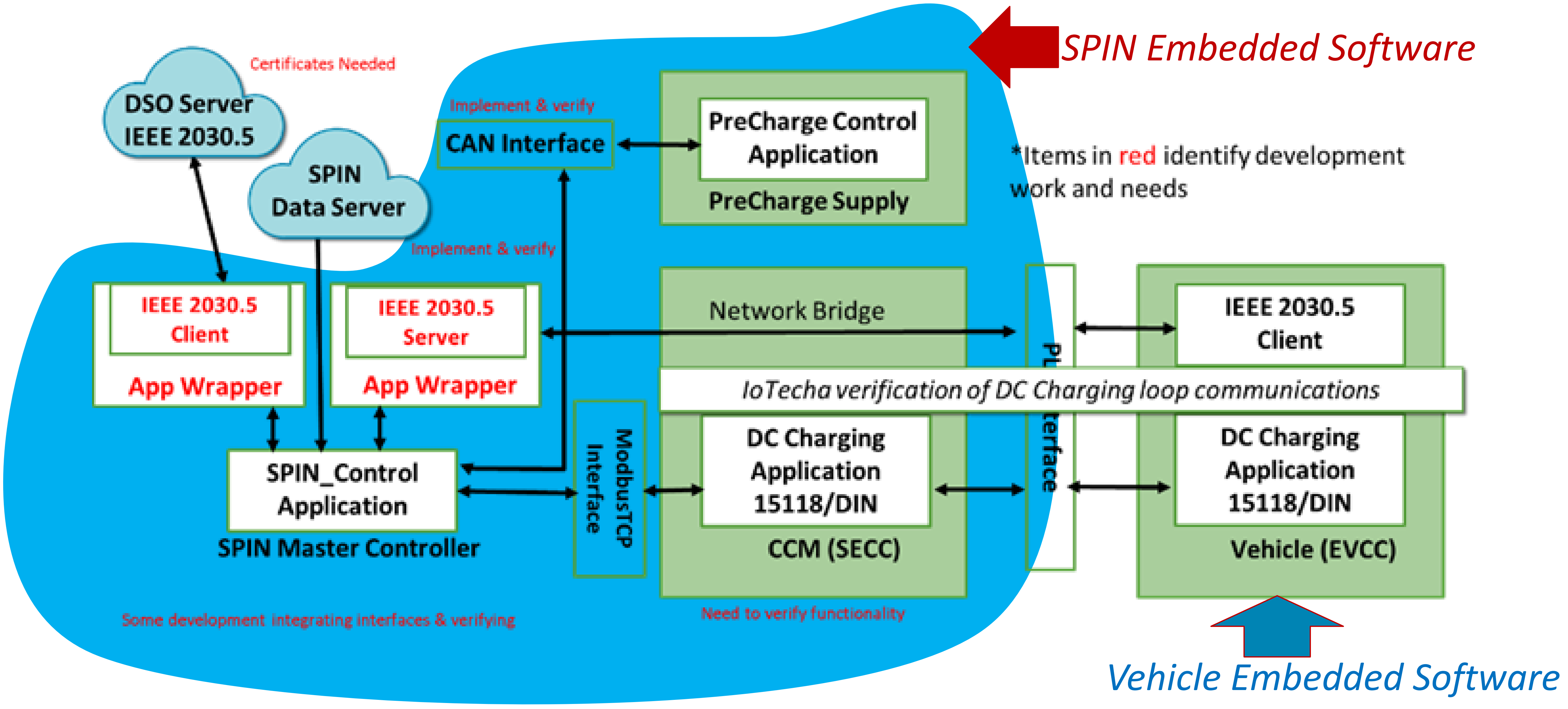
- BP3 Go-Ahead Approved
- Re-defined Battery Durability task – FCA/NREL SOW approved
- Coordinated V2G DC Component/Software Implementation
  - DSO Server (Kitu Systems)
  - SPIN Master Controller (FPC/EPRI)
  - DC Control Communications Module/ CCS Connector/SECC PLC Module (Rhombus/FPC/IoTecha / EPRI)
  - EVCC/PLC Module (FCA/IoTecha)
- Functional Architecture, Requirements, Implementation at subsystem level complete

On-Vehicle: Completed System Demo, Published Public Results
Off-Vehicle: Power Electronics, Local Control, Analytics and UI Prototypes Verified

Key V2G Use Cases: Integration and BMS / Microgrid Control and Communications



Technology: DC V2G Comms Architecture - Final



Footprint of the Project Across the US

V2G Pack Test Cycle

The intent is to provide 2 Pacifica PHEV Battery Packs for testing. One pack will be run with just the driving duty cycles and the other with the residential V2G cycles to provide a comparison.

Notes:

- Pack 1 is the V2G pack.
- Pack 2 doesn't discharge at home so only takes an hour to recharge.
- Cycles will be run continuously 24/7

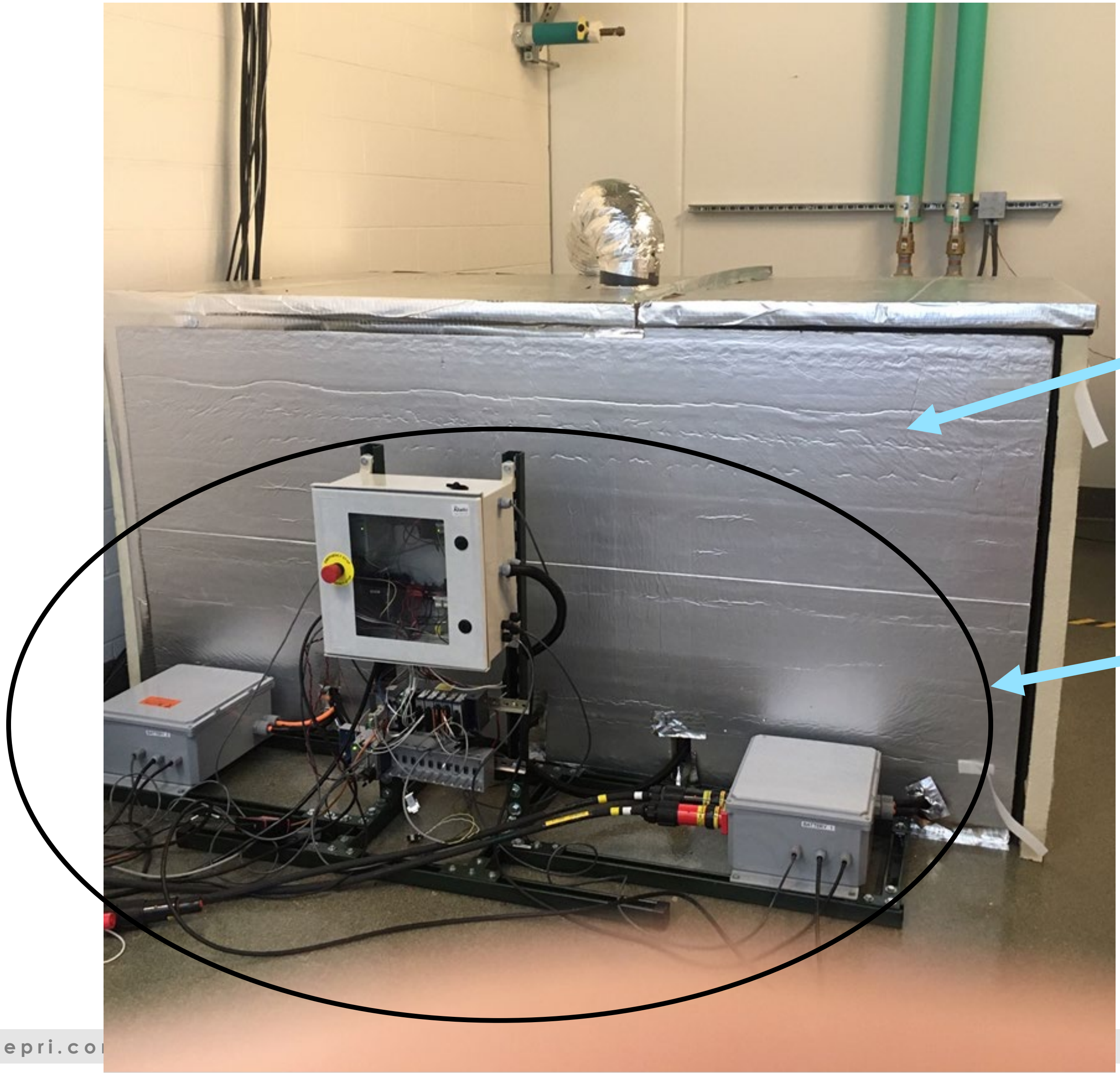
	Pack 1	Pack 2
	hours	
Work	-	-
Drive home	0.5	0.5
Discharge at home (10kW)	1	0
Charge to 100%	2	1
Wait (key cycle – contactor open)	1	3
Drive to work	0.5	0.5
Charge (50% to 100%)	1	1
Total time/cycle	6	6

Cycle Discharge ~ 15 mi					
	Cycle	Time (hrs)	Distance (mi)	Energy Throughput (kWh)	Net Energy (kWh)
CD	CD1 City	0.3811	7.44	3.96	2.24
	CD US06	0.1667	8.01	5.27	2.81
CD total		0.5478	15.45	9.22	**5.05**
Total pack kW					11.8
Usable energy after both drive cycles (kW)					**6.75**
Proposed discharge power (kW) - available for DER					2
DER duration (hrs)					3.375

RPT* every 28 days (4 weeks)
RPT will consist of a C/3 capacity cycle and HPPC

**RPT = Reference Performance Test*

Battery Pack Testing Setup: Insulated Enclosure with Controls and Instrumentation



Insulated Enclosure

- CAN Communication
- Relays
- Current Shunts
- Emergency Shutoff
- Data Acquisition

Battery Pack Thermal Management: Air handling system, 30°C

Response To Reviewers Comments

Reviewers Comments

- "Based on the Milestones presented, Phase 3 of the project has recently started and is estimated to be completed in one year. In the reviewer's opinion, the proposed timeline for budget period 3 is extremely aggressive, particularly considering the presence of significant verification, data collection, and post processing."
- "The reviewer is concerned that managing such a large team could produce further delays in the project."
- …"The task of assessing the impact of V2G on PEV battery capacity and impedance should not be overlooked in terms of time and effort required."

Response

- Timeline: This has turned out to be correct, primarily due to the delays encountered setting up the battery testing (9 months) and then the COVID19 shelter in place.
- Team involving large organizations ultimately distills down to core technical team comprising of individuals who have worked together on a number of projects together over several years and multiple programs. The relationships, project deployment process and the communications methods are established to create a high-trust, high-performance team spanning organizations.
- Battery durability testing remains the final, very important and uncompleted task. However, the team is confident that once the 'shelter in place' order is sufficiently relaxed in Colorado, this testing can commence to complete in 6 months.

Collaboration and Coordination

Prime	EPRI ELECTRIC POWER RESEARCH INSTITUTE
Smart Power Integrated Node (SPIN)	FLEXPOWER CONTROL Power Your Way; KITU SYSTEMS
Grid/SPIN/PEV Communications	EPRI ELECTRIC POWER RESEARCH INSTITUTE
Power Electronics Test & Demonstration	OAK RIDGE National Laboratory
On-Vehicle Integration	FCA FIAT CHRYSLER AUTOMOBILES
EV Battery – Durability Assessment	NREL NATIONAL RENEWABLE ENERGY LABORATORY

Collaborative Team Includes Expertise from Subject Matter Areas and Proven Capabilities

Remaining Challenges and Barriers

Understanding of impact to vehicle battery durability and cycle life

- Assessment of PEV Battery impacts from V2G within specified SOC boundaries to mitigate or avoid degradation of capacity, impedance, etc. based on PEV battery capacity constraints

Standards based end to end V2G/DER integrated system communications / controls

- Testing and certification of interoperability for validation required for wide adoption of V2G application standards

Determination and verification of value-added use cases for V2G/DER application

- Assessment of ZNE and Microgrid operational capabilities and benefits – follow on research funding required

Challenge: Integrate End to End V2G System Functions on Grid, SPIN System and PEV with evolving SAE V2G Standard

Future Work

BP3 – DC V2G System Integration and Test

- Integration of SPIN DC charging / discharging – and SPIN to vehicle V2G interface/control communications
- Demonstration and functional validation to control DER/V2G power flow for maximum local utilization of PV generation
- Validation of analytics/algorithms to maximize V2G/DER
- Verification of battery impacts from utilization for V2G
- Correlate AC and DC V2G project findings

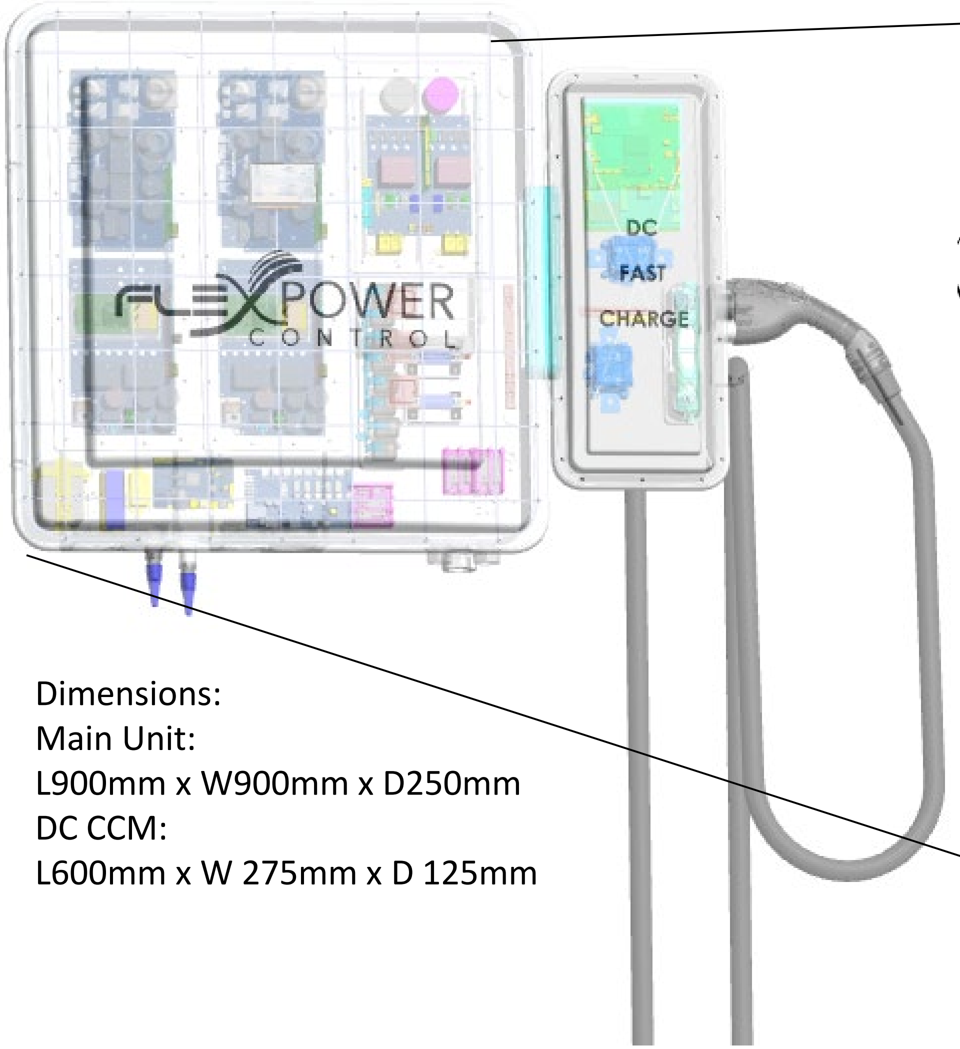
Proposed Future Work

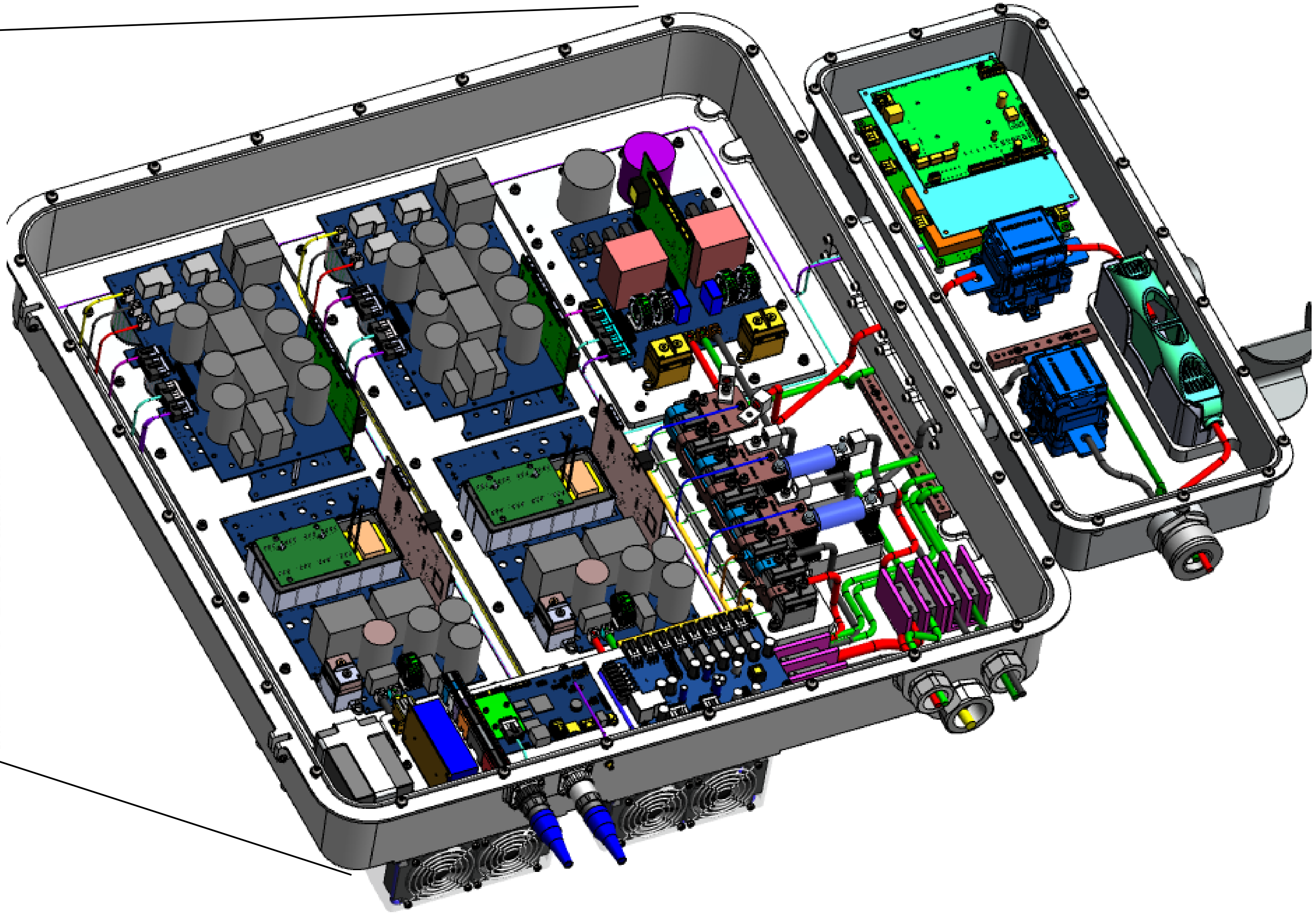
- Smart Inverter Communications and Functions for AC and DC Charging / Discharging applications
- Expanded evaluation of integrated V2G/DER attributes and cost effectiveness with utility stakeholders – leverage SPIN product development program (DOE 1740) to extend into utility supported evaluation pilot programs
- Assessment of ZNE and Microgrid operational capabilities and benefits from V2G/DER – research funding needed

Future Work Ongoing on Two Additional Follow-on Projects: CEC 16-054 with Ecosystem Software; SETO EE0008352: Proof-of-Design

SPIN Commercialization Continuing Through other Funded Research

SPIN CAD Layout





Dimensions:
Main Unit:
L900mm x W900mm x D250mm
DC CCM:
L600mm x W 275mm x D 125mm

Summary

On-Vehicle (AC) V2G technology demonstration completed

- Completed demonstration and verification of AC On-vehicle V2G application of SAE/IEEE2030.5 protocols
- Standards interoperability verified between TMS/EVSE (Bridge)/EV (Honda & FCA PHEVs)
- Follow-up discussions to incorporate AC V2G in the California DER discussions underway, with this project being the primary technical foundation (CPUC Rule 21 Working Group 2)
- Final report submitted Jun 2018 /Released Mar 2019 through CEC https://www.energy.ca.gov/2019publications/CEC-500-2019-027/index.html

Off-Vehicle (DC) V2G/DER system integration progressing

- Implemented controls software architecture for SPIN DC Control Communications Module (CCM) and EV V2G communications module interoperability
- BP3 milestones are completion of SPIN V2G/CCM system integration with FCA PHEV and NTRC lab testing/demonstration - and evaluation/assessments of FCA PHEV Battery Packs for durability by NREL

Emphasis on verifying V2G/DER open standards with key use cases

- Validation of V2G functionality as a viable DER asset through application of SAE/IEC/IEEE standards

On-Vehicle V2G Technology Demonstrated, Grid Interface Comms Leveraged for Off-Vehicle V2G Integration; Learnings Applied to Follow-on Projects

Technical Back-Up Slides

BP3 Task Schedule Overview

V2G Distributed Energy Resource (DER) Integration Testing and Evaluation

OEM Vehicle DC V2G Communications Implementation and Verification

Preliminary Vehicle and SPIN Communications Interface and Control Simulation Verification

Use Case Communications/Control/Duty Cycle Testing (preliminary test verification prior to start of demonstration)

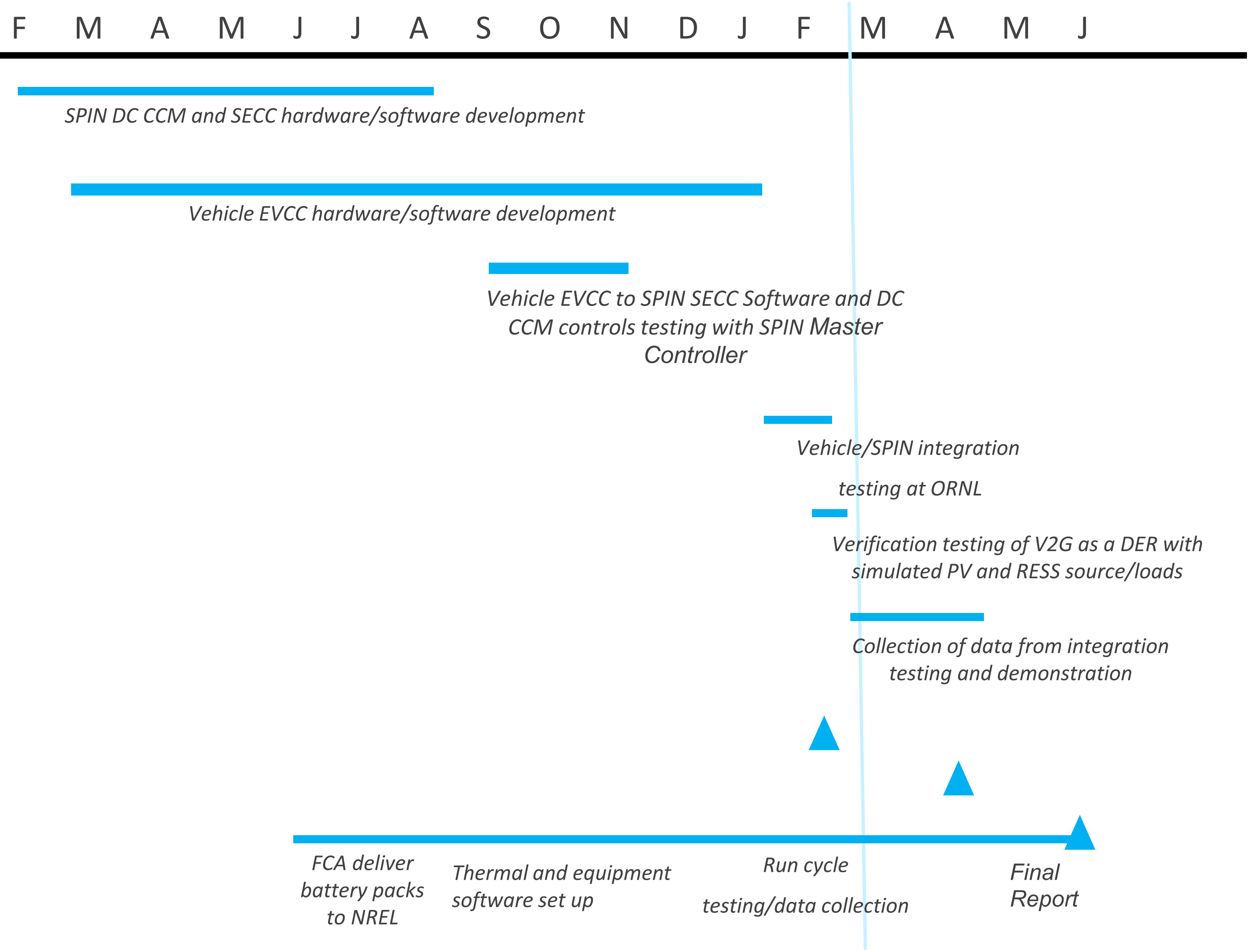
Conduct V2G Lab Demonstration

Data Collection and Analysis

V2G Demonstration Progress Review

Demonstration Report

NREL Battery Pack Durability Characterization and Test Report



Technology Development – DC V2G Functionality Implementation

- **SAE J2847/2 DIN 70121 on SPIN**: Received the IoTecha SECC module at **Rhombus**. Hardware Integration complete, SW integration *in progress* with IoTecha support.
- *Implementing* the Modbus register map definition from IoTecha for interface communications between the IoTecha SECC (MEVSE) and the SPIN Master Controller.
  - SECC provides the J28487/2 (DIN 70121), and PLC bridge to EVCC
  - The DIN 70121 is being amended to provide the discharge messages in harmonization with ISO/IEC 15118 Edition 2 - New feature in the standard being driven by this program.
- **SAE J2847/2 DIN 70121 on PEV**: IoTecha is providing the EVCC module to **FCA** for integration into the vehicle, including J2847/2 (DIN 70121) and CAN translation to the vehicle charge controller – new configuration board for on vehicle DC Charge integration
  - The IEEE2030.5 Client /Server software being provided by EPRI – between Master Controller and EV EVCC. (IEEE2030.5 Server code completed by EPRI. Integration testing with Master Controller underway)
- Actual V2G power flow can only be implemented and tested with all systems *integrated* at ***ORNL NTRC***. FCA limited to just being able to test DC *charging/discharging*.

DC V2G DIN 70121 Implementation – SPIN and EV

- **SPIN - PEV Communications**: Utilizing the IEEE 2030.5 version 2013 software from previous CEC AC V2G Transformer Management System (TMS) program.
  - Investigation/adoption of the DC V2G commands from the on-vehicle V2G TMS.
  - Analysis and charge/discharge/schedule initiated by SPIN Rack system
- **SPIN System Components**: **EPRI** constructed a bench top communications system including the Master Controller, DC CCM pre-charge module, IoTecha SECC module, and the IoTecha EVCC module.
  - Foundation for system integration and test, validated software ahead of the system, will help accelerate system integration/test at ORNL NTRC
  - IoTecha provided the SECC module network bridge to PLC for communications to the EVCC module.
  - Validated the interoperability between the IoTecha SECC and IoTecha EVCC modules for SPIN to vehicle communications.

Planned Activity – System Integration at ORNL NTRC – Stalled due to COVID19 Shelter in Place Orders

- Upon completion of the bench testing the coding is to be imported into the hardware (vehicle and Rack System at NTRC) for system integration, testing and demonstration at ORNL NTRC.
- Complete control communications implementation and testing of SPIN DC Convenience Charge Module (CCM) and the PEV (FIAT 500 EV)
- Complete CCM power electronic system controls and communications testing at Rhombus.
  - Incorporated the J1772 conductive charging safety protocol and the IoTecha SECC with the DIN 70121 DC charge and amended discharge control protocols.
  - DC CCM and Combo Coupler Assembly transitioned to ORNL for integration with the Rack System and V2G vehicle system integration and demonstration

SPIN – Ongoing Technology /Product Development Commercialization Pathway

EPRI Technology Innovation Program

SPIN Concept Design / Spec

CEC EPC-14-086: Distribution System Constrained V2G Services

- Core V2G Functionality refined, implemented, verified
- OEM Interfaces Defined for V2G and Smart Inverters
- Projects involving on-vehicle V2G planned
- Within SIWG, learnings being transferred for on-vehicle inverters to be Rule 21 compliant

DoE EE0007792: On- and Off-V2G Performance and Grid/Battery Impacts

- SPIN Hardware and Base Software Developed
- Power Flow Verification
- Verified for DC V2G implementation
- Battery test protocol and impacts assessment

CEC EPC-16-054 – Ecosystem Integration

- External System Integration,
- End to End Functionality Development
- Integration and Test for DSO, Microgrid, and Standalone BMS integration
- Off-board DC inverter as smart inverter, integrated with PV and Storage
- Leveraging SPIN developed from DOE EE7792 Program

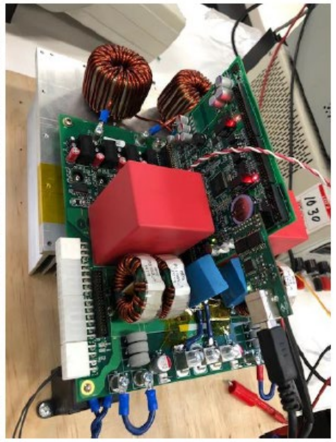
DoE EE0008352: SPIN Productization

- SPIN as a product with Rhombus as the technology developer
- Wide Bandgap devices – high efficiency, broader temperature range, compact
- PV/EV/Storage Integrated Package
- Significant partner interest in offering this package. Prime application for addressing distributed resilient systems

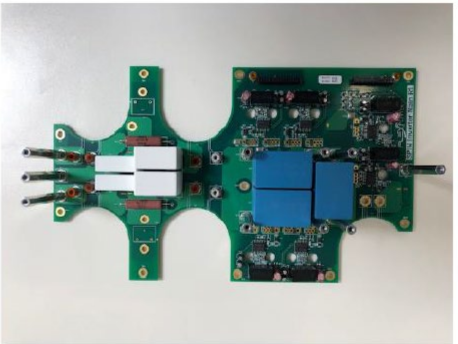
Scope of EPC-16-054

Commercialization-Intent Hardware Design Complete – First Functional Samples in 4Q2020

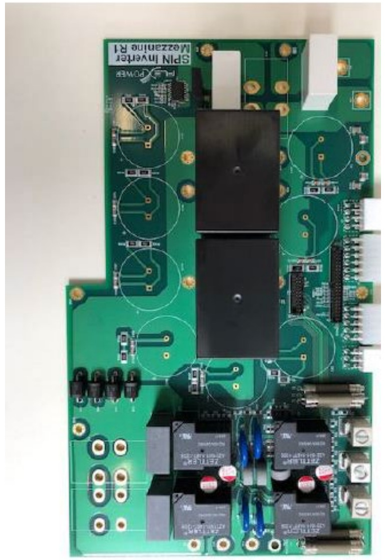
SPIN Bidirectional DC Charger



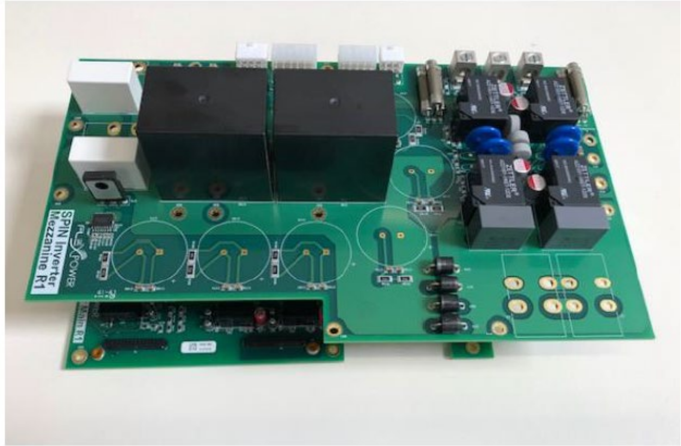
Power Board



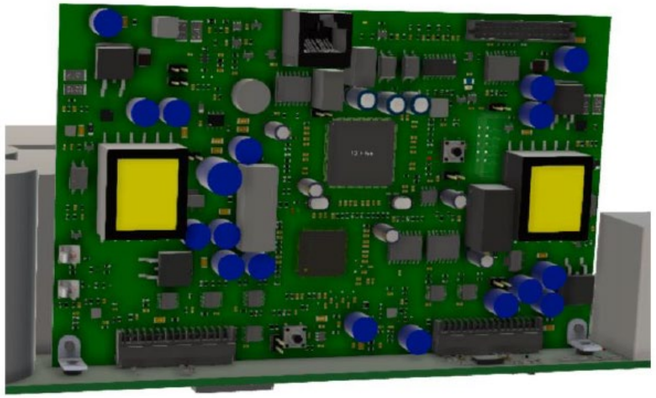
Mezzanine Board



Power Section



Dual-Active Bridge



Optional DC CCM