2010 DOE Vehicle Technologies Program Review

Advanced Integrated Electric Traction System

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General Motors
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Project ID # APE014

Overview

Timeline

- Start - October 2007
- Finish – May 2011
- 70% Complete

Budget

- Total project funding
  - DOE - $7.9M
  - GM - $13.5M
- Funding received in FY08, FY09, and FY10
  - GM - $5.0M

Barriers

- Power Module packaging technology – joints, interconnects
- Switch technology
- Capacitor temperature capabilities
- Thermal management
- System cost

Targets

- Meet DOE 2015 Goals – Cost $12/kW, Mass 1.2kg/kW, and Volume 3.5 kW/L

Partners

- Ames Laboratory, Arnold Magnetics, AVX, DuPont, Infineon, Semikron, and Oak Ridge National Laboratory

Relevance - Project Objective

Overall FY08-FY11

- Develop and demonstrate advanced technologies for an integrated ETS capable of 55kW peak power for 18 seconds and 30kW of continuous power.
- The ETS is to cost no more than $660 (55kW at $12/kW) to produce in quantities of 100,000 units per year, should have a total weight less than 46kg, and have a volume less than 16 liters with a nominal 105°C coolant and >93% efficiency.
- The cost target for the optional Bi-Directional AC/DC Converter is $375.

May ’09 to May ’10

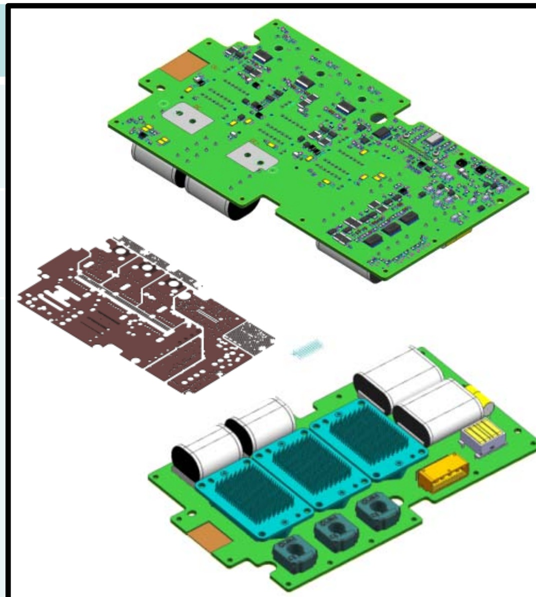
- Complete design of ETS, Converter, and build

Milestone

Timing	Milestone
July 2008	Completion of Phase 1 Concept Design/Integration Study – Investigate/assess technologies and design concepts to meet HEV, PHEV, FCV, and EV. Go/No-Go Decision for initiate Phase 2.
June 2009	Preliminary Design Review – Finalized concept design for integrated electric traction system.
September 2009	Critical Design Review – Final design review before ordering parts for build.
April 2010	Environmental Test Setup –Design and fab test chamber.
June 2010	Complete AIETS Build.
October 2010	Electrical Verification - Electrical testing of Electric Traction System to requirements this includes a bench, dyne, and EMC radiated and conductive.
March 2011	Final Test Report – Documentation of all Electric Traction System test data generated

Approach

Description	Reason
Develop accurate system specifications.	Reduce cost and increase reliability of system.
Motor - increase power density using multi-phase topology.	Reduce cost, less material needed for same power.
Board centric power electronics – heavy copper board (power and signal) with surface mount and press fit parts only.	Increase flexibility to adopt to vehicle applications, simplify manufacturing process, while improving electrical performance. Entire inverter on circuit board, up integration of bulk capacitor, elimination of lead free solder joint with press fit pins, and reduced inductance.
Power module – improve design, with new switches with on-chip current and temperature sense, reduced packaging inductance, and improved joint technology.	Integrate/increase functionality to reduce cost and increase reliability. Increase system protection for over current and temperature. Improve joining technologies to allow >175C junction temperature and will allow in the future increasing to >200C. Enable packaging to support future GaN/SiC switches.
Dc bus capacitor – eliminating housing, minimizing potting and bus structure	Reduce cost by eliminate non value added material and increase flexibility of scaling capacitance to system needs.

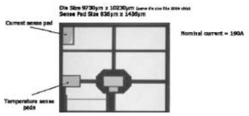


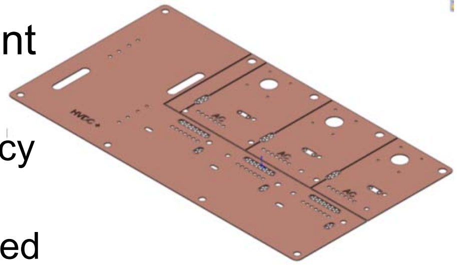
Heavy Layer Circuit Card Technology

Strategy

- Use results of Phase I technology investigations and assessments and execute Phase II Development/Demonstration
- Phase II Development/Demonstration (8/08 – 5/11)
  - Develop detailed design of an Advanced Integrated ETS
    - Ensure compatibility with all vehicle requirements
    - Simplify and integrate ETS to meet technical targets
    - Work closely with suppliers and leverage National Lab materials, packaging, and analysis work
    - Applying learning from GM's electrification experience
    - Verify component technologies and document
  - Build Advanced Integrated ETS and characterize (6/10 – 1/11)
    - Prove the viability of the technologies through 7 tests designed to assess hardware performance for temperature, vibration, and EMC

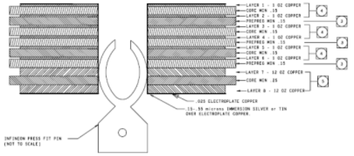
Accomplishment – Technology/Component Development

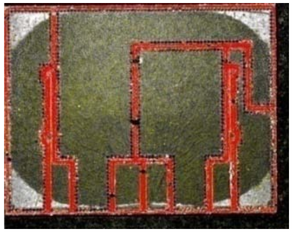




Performed detailed analysis and testing to verify technology/component performance

- IGBT with on chip current and temp sense has been tested for accuracy over operating temperature, current, and voltage
- Heavy copper board and press fit pin connection, insertion force, formed joint, circuit noise issues, layout constraints, and current capability
- Power module joint technology tests (1800 cycles)
  - Sintered joints with different combinations of substrate (AlN, Si_3N_4 and Al_2O_3) and base plate, metal injection molded Cu cold forged Al, material being evaluated using three sources
    - Critical factors in successful joint are, plating, thickness of paste applied across joint, joint area, and uniform pressure
  - High temperature solder
- Developed capacitor capable of meeting high temp environment using polypropylene film and has been verified through testing
  - Film thickness, width, metallization, and resin evaluated
  - Testing
    - Verified through life testing at temperature and voltage
    - Humidity, temperature rise with current, ESL, and ESR

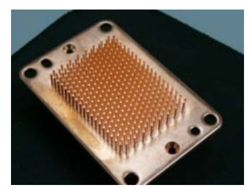


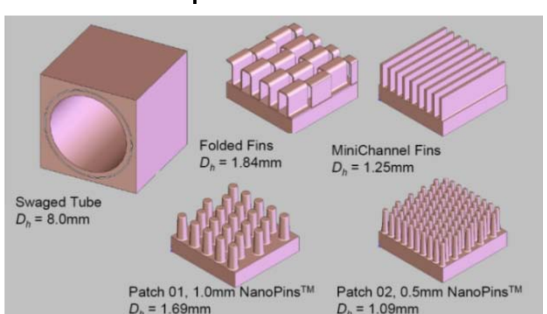


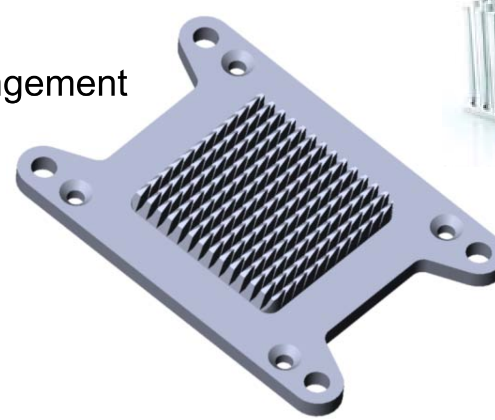
Accomplishment – Thermal

Cooling methodologies have been studied and compared for cost and performance

1. Copper pin fin MIM heatsink with AlO or AlN Substrate
2. Advance copper pin fin
3. Copper pin fin brazed to bottom copper layer of substrate
4. Forged Pin fin with integrated ceramic and top copper layer
5. Normal Flow Microchannel Heatsink with soldered DBC
6. Normal Flow Microchannel etched in bottom copper layer of DBC
7. Integrated Microchannel parallel flow with DBC
8. Integrated Microchannel parallel flow with ceramic on two sides and devices on two sides
9. Indirect jet impingement directly on substrate
10. Substrate with integrated heat pipe
11. Direct liquid immersion cooling
12. Direct Jet Impingement on silicon
13. Microjet Array
14. Double sided
15. Synthetic Jet
16. Optek's OptoTherm
17. Nonlinear fin pattern with normal flow impingement

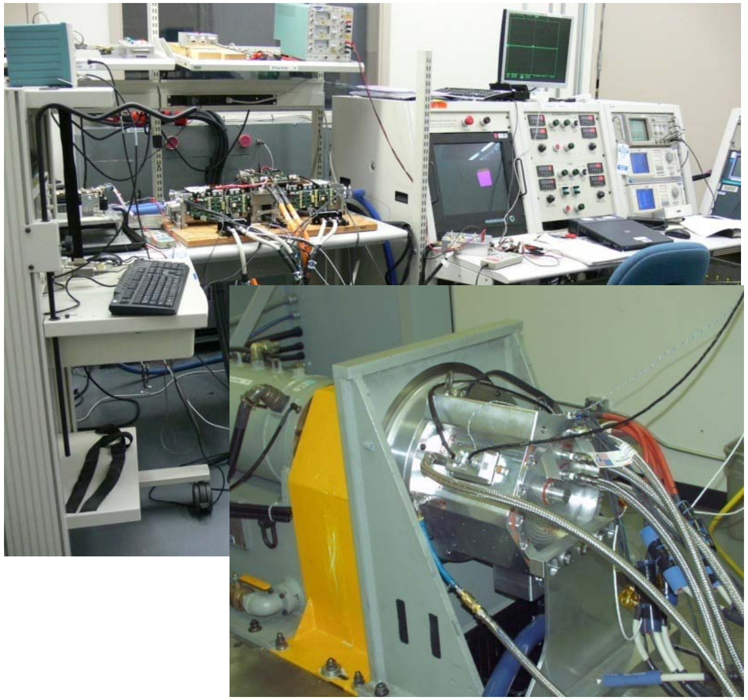


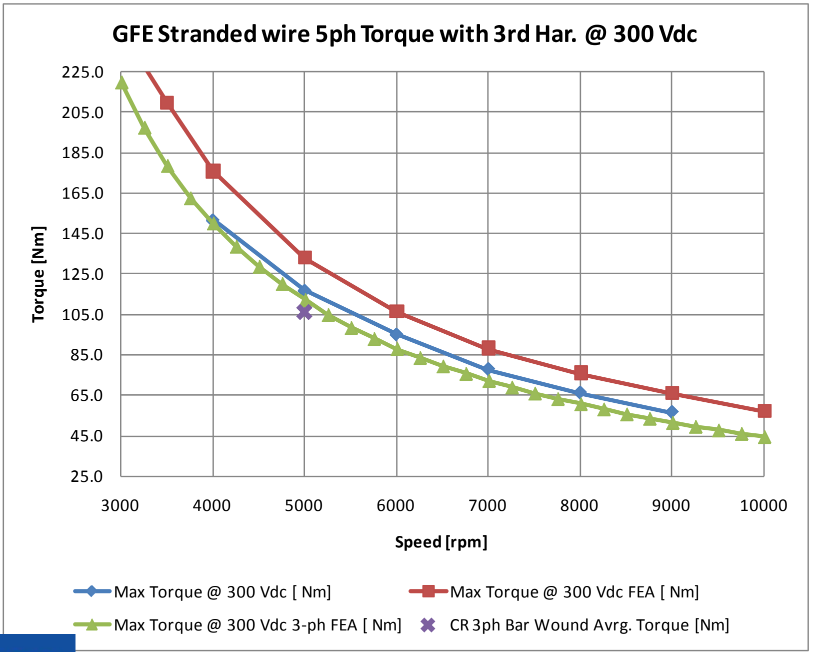




Accomplishment - Multi-Phase Controls

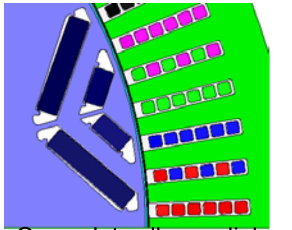
- Multi-phase controls development dyne test bench implemented. Prototype PIM, 6-phase and 5-phase motor hardware built to support development activities.
- Method developed to obtain the optimum fundamental and third harmonic current commands and flux linkages for multi-phase machines over the entire torque-speed region by means of voltage source FEA models. This allows for machine optimization without the need for prototype hardware.
- For machine characterization, a method was developed for obtaining the optimum current commands which requires manipulation of only two control variables- a significant reduction in controls complexity.
- The derived fundamental and 3rd harmonic current commands for a stranded wire version of the final DOE 5ph bar wound motor have been established. 5ph over-modulation functions were developed and tested.





- The Back EMF of the motor was measured and determined to be in line with FEA results. The machine meets the required low speed torque reqt (270Nm) with the available PIM peak phase current (185Arms).
- Performance of the machine in the peak torque and field weakening regions up to 9,000 rpm has been completed.
- HV bus ripple tests comparing 3-phase vs 5-phase systems were completed using GM's two-mode NiMh pack. A reduction in ripple in the 5-phase configuration was verified. The addition of 3rd harmonic content may be a significant factor in reducing capacitor current ripple levels.
- 5 phase ETS efficiency data in line the project objectives.

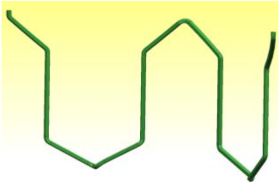
DOE Multiphase Motor Accomplishments



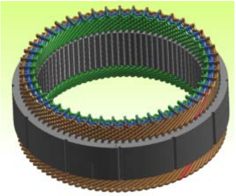
Open slots allow radial insertion of fully-formed coils eliminating the need to form the end-turns after insertion.

Motor designs and builds for dyne testing, FEA verification and controls development:

- Rewound the stator of motor used in the FCEV Equinox to 6-phase configuration to provide first multiphase machine experience.
- Redesigned and remade the stator of the same motor to 5-phase and used with existing rotor to provide first 5-phase machine experience.
- Designed an optimized, application-specific, radial insertion bar-wound 5-phase machine, and built an expedited version with a traditional stranded wire stator to provide an early approximation of the final machine.
- Completed mechanical design including thermal and stress analyses of the radial insertion bar-wound 5-phase machine to minimize manufacturing and tooling costs.
  - ➢ Developed dual coil concept to reduce quantity of welds by 50%.
  - ➢ Developing insertion tools and stator build processes.
  - ➢ Forming stator coils and fabricating slot liners.
  - ➢ Rotors are complete and all other parts and materials are available.



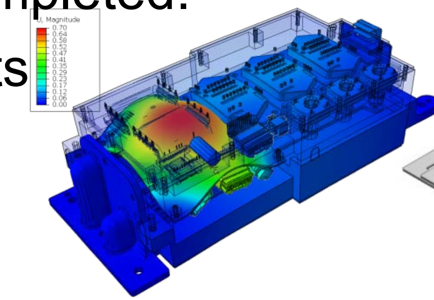
Dual coil for radial insertion and weld reduction

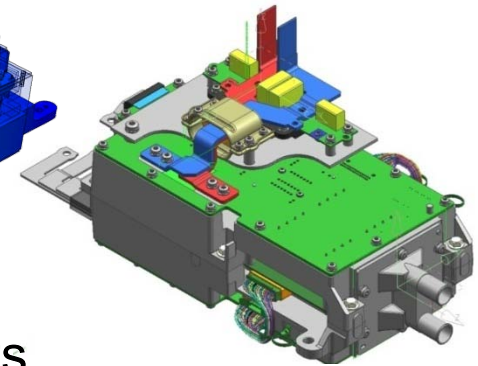


5-phase bar-wound stator with one-half as many welds

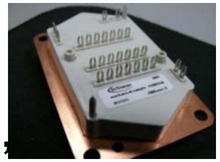
Accomplishment - Inverter

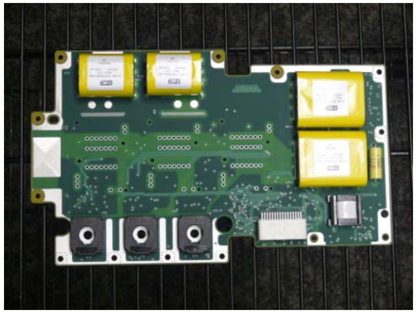
- Thermal analysis of the inverter completed.
  - All temperatures are within limits
- Modal and CFD analysis complete
  - Meets GMW3172



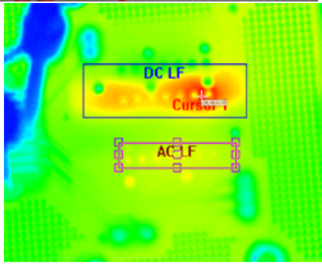


- Completed design, released drawings, ordered parts, manufacturing assembly instructions and fixtures developed
- Power Module, Gate Drive (includes DC capacitance), and control card have been tested and verified



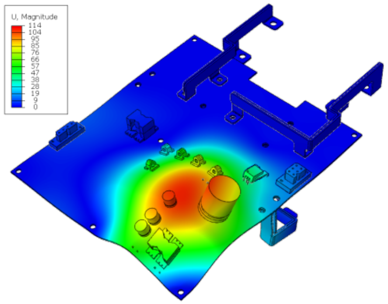


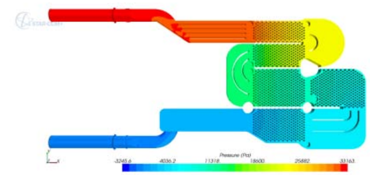
- First electrical unit built up on test manifolds for electrical testing
  - Interconnects, dc bridge, and high power through system

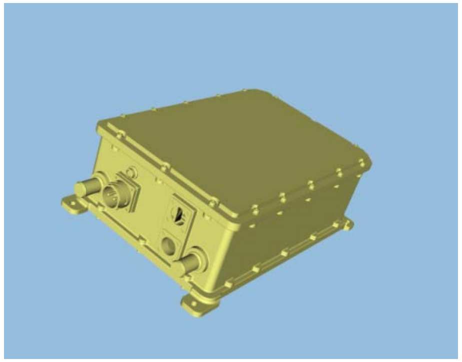


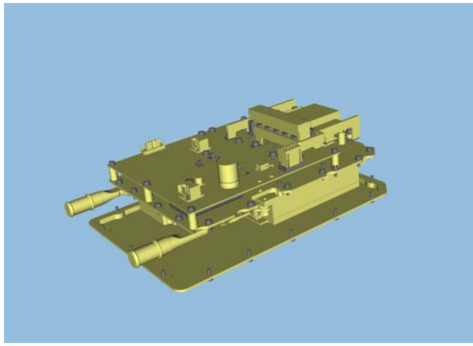
Accomplishment - Charger

- Modal and CFD analysis complete
  - Meets GMW3172
- Built early proto hardware
  - Functionality has been verified
- Completed design, released drawings, ordered parts, manufacturing assemble instructions and fixtures developed
- Established collaboration with EPRI for battery to grid





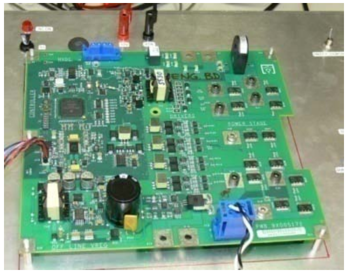




DC Output

Control Signal

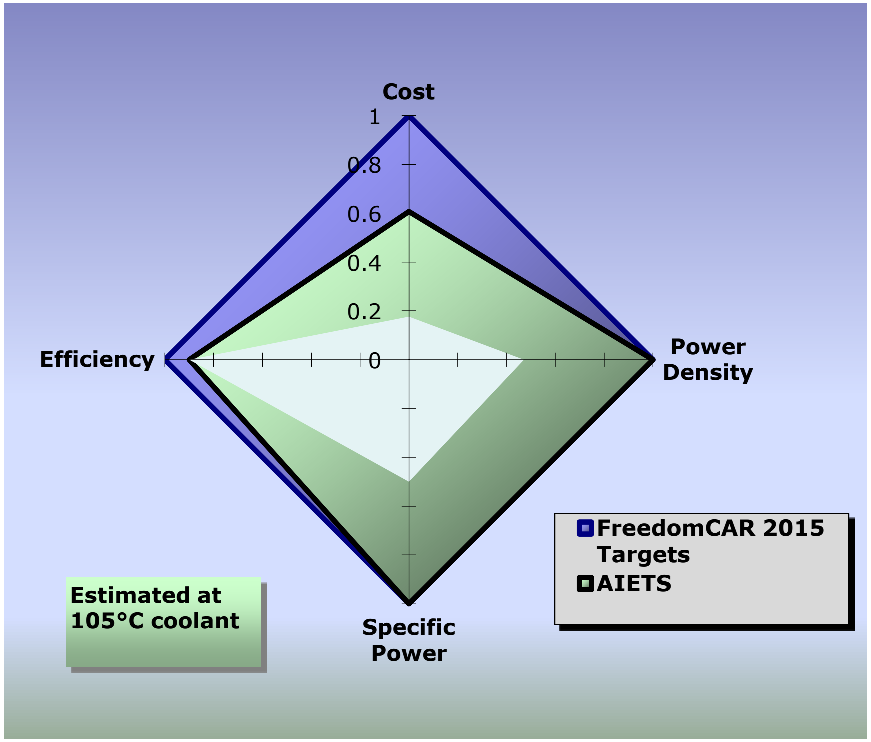
120Vac input, 242VDC - 10Amp, 2.4kW Charging Mode

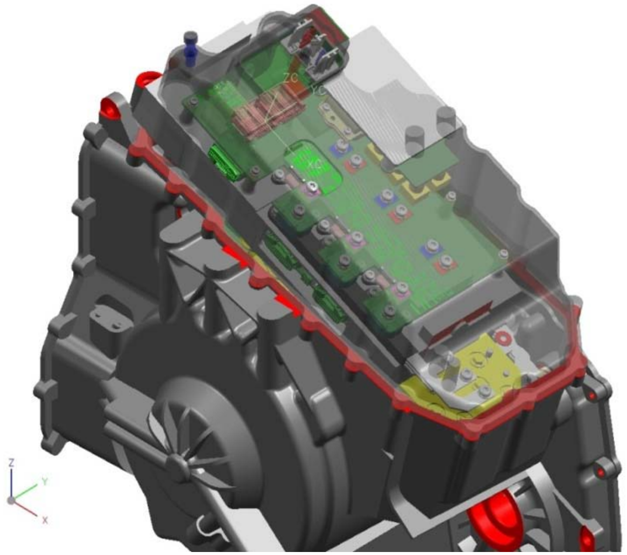


AC Input Current
PF=.99

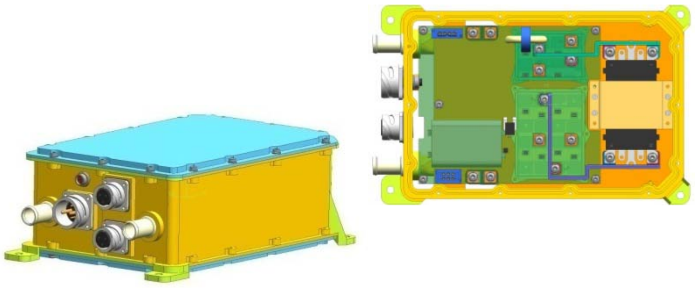
Accomplishments - Program

- **Technologies assessed : 29**
- **Configurations/Types: 36**
  - **Topologies, bus, EMI filtering, components, and concepts**
- **Patents: 31**
- **Compatibility with vehicle production**





Integrated Motor and Inverter



Charger

Collaboration

- AIETS GMATC
  - Systems
  - Motor
    - Magnets: Arnold Magnetics, (S/C) Hitachi Metals, TDK, Chevron Mining
    - Lab Support: Ames (materials)
    - Materials: Mitsui-High-tec, **L.H. CARBIDE,** Hoganas, Tempel, & IAP
  - Inverter
    - Power Module: Infineon &Semikron
    - Capacitor: AVX (S/C)
    - LAB Support: ORNL & NREL (materials, joining technology, switches)
    - Materials: DuPont, Kyocera, Murata, &Curamik
  - Charger
    - Power Module: IXYS, Teledyne
    - Capacitor: ASC
    - Applications/Usage: EPRI

GM, Suppliers, and National Labs cooperation has been of great benefit to the program and has provided input into other existing Vehicle Technologies projects.

Proposed Future Work

- FY10
  - Complete build of ETS and Charger
  - Start characterization testing
    - Bench, dyne, EMC radiated and conducted, step stress, vibration, and thermal survey
- FY11
  - Complete characterization testing of ETS and Charger
  - Verification Tests with Government Lab
  - Issue final report

Summary

General Motors is applying a systems approach to the ETS and how it is used in vehicle applications

- Relevance
  - Meet DOE 2015 targets
- Approach/Strategy for Deployment
  - Proper requirements, improve power density through topology, board centric design, and automotive regimented development
- Technical Accomplishments and Progress
  - Completed design and parts on order
  - Analysis and component testing has been done with results being provided back to suppliers
  - Early proto hardware in tests to confirm electrical performance
    - Stranded 5-Phase Motor, Inverter, and Charger
  - Started build of units for characterization testing
- Collaborations and Coordination with Other Institutions
  - Extensive work being done with suppliers and National Labs that also has provided input into other existing Vehicle Technologies projects
- Future Work
  - Complete build and testing

GM