Advanced Integrated Electric Traction System

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Project ID: ape_09_smith

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Overview

Timeline

- Start - October 2007
- Finish – May 2011
- 45% Complete

Budget

- Total project funding
  - DOE - $7.9M
  - GM - $13.5M
- Funding received in FY08 and FY09
  - GM - $3.3M

Barriers

- Thermal management
- Switch technology
- High Temp Capacitor
- Motor mass and cost
- Rare earth magnet material cost

Targets

- Meet DOE 2015 Goals – Cost, Mass, and Volume

Partners

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

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Project Objective for FY08 – FY11

- **Develop and demonstrate advanced technologies for an integrated ETS capable of 55kW peak power for 18 seconds and 30kW of continuous power.**
- **Meet DOE 2015 Targets**
  - ETS that can accommodate a variety of automotive platforms and the design should be scalable to 120kW peak power for 18 seconds and 65kW 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.
  - The cost target for the optional Bi-Directional AC/DC Converter is $375.
  - The goal is to achieve these targets with the use of engine coolant at a nominal temperature of 105C.
  - The system efficiency should exceed 90% at 20% of rated torque over 10% to 100% of maximum speed.

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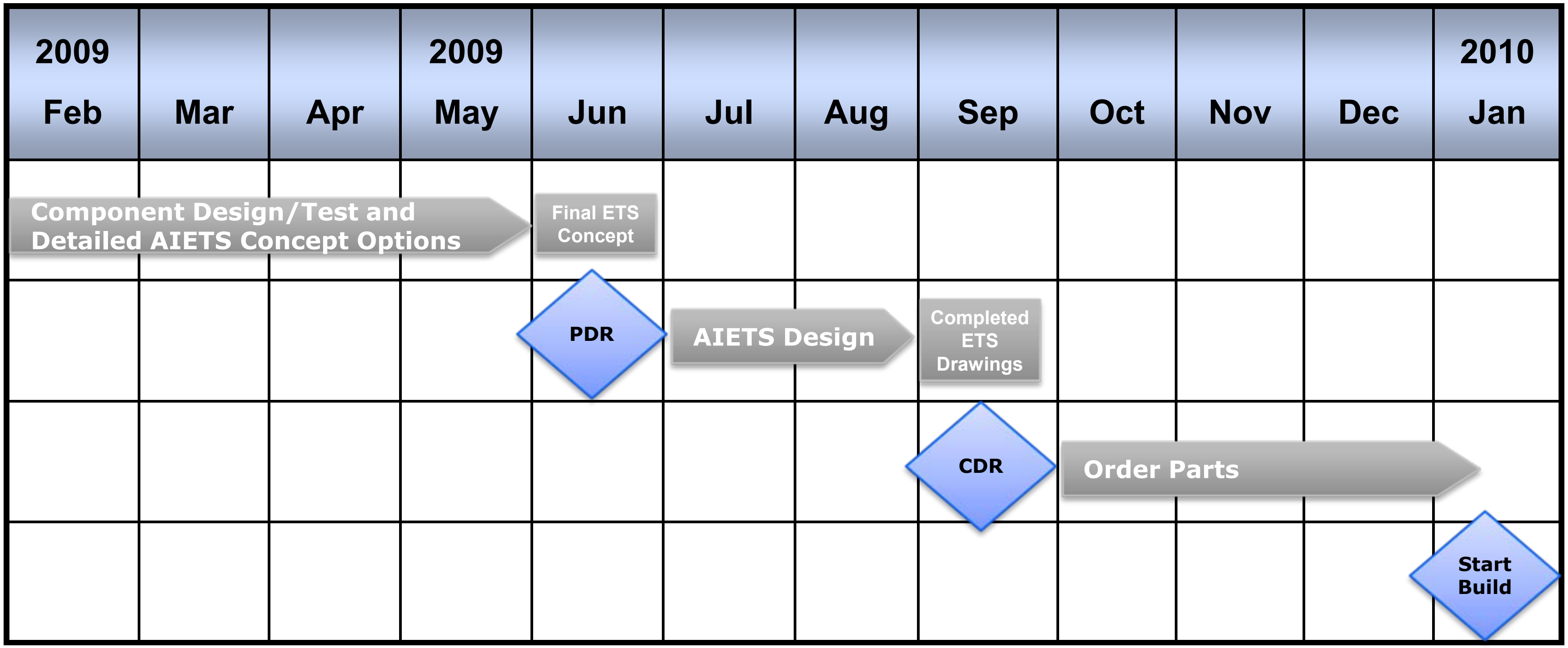
Timeline



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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

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Technical Approach for FY09 and Beyond

- 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
    - Work closely with suppliers
    - Applying learning from GM's electrification experience
  - Build Advanced Integrated ETS and characterize
    - Prove the viability of the technologies through 7 tests designed to assess hardware performance for temperature, vibration, and EMC

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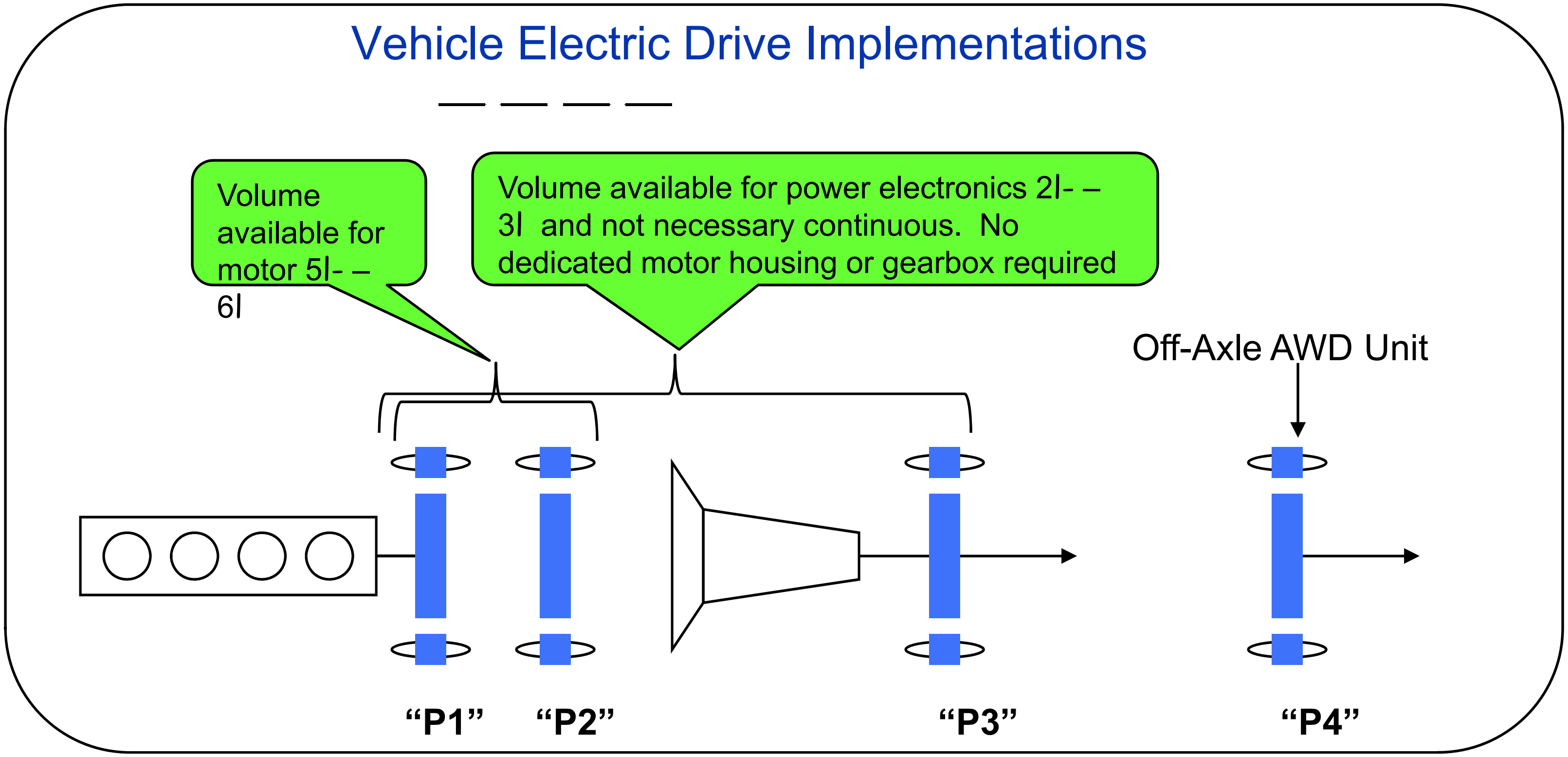
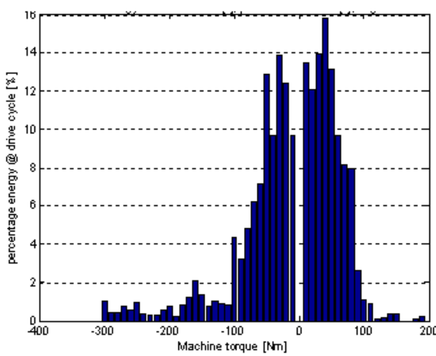
Accomplishment – Vehicle Flexibility



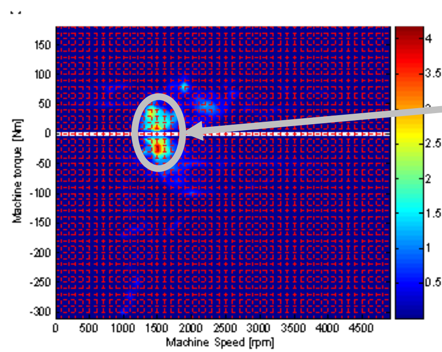
To maximize number of platforms for ETS we considered all potential vehicle implementations

Accomplishment – Requirements

- **Properly defined requirements that allow for vehicle flexibility, high reliability, and low cost is the most significant contributor to the program success**
  - **Defined electric drive modes of operation**
  - **The electric machine output performance requirements were developed based on GM's hybrid vehicle system model**
  - **Determine operating points were greatest system efficiency needed**



Machine Torque/Energy Usage Histogram



Energy –Weighted Torque Histogram

Area of most interest for ETS high efficiency operation

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Accomplishment – Trade Study

- Established common requirement baseline and ETS operating points for evaluation.
- Established the major criteria and sub-criteria to be used for scoring. Set scoring scale for each sub-criteria.
- Performed Pair-wise weighting
- Built necessary cost, volume, weight models
- Ran Simplorer and motor models to quantify performance criteria.
- Used consensus method to score non-quantifiable criteria.

Trade-Off Study: DOE IETS Topologies Criteria	Performance	Packaging	EMC	Reliability	Scaleability/ Design Flexibility	Cost	Risk and Timing							
Performance		0.0	0.0	0.0	0.0	0.5	0.0							
Packaging	1.0		0.0	0.5	0.0	1.0	0.0							
EMC	1.0	1.0		1.0	0.5	1.0	0.5							
Reliability	1.0	0.5	0.0		0.0	1.0	0.5							
Scaleability/ Design Flexibility	1.0	1.0	0.5	1.0		1.0	0.5							
Cost	0.5	0.0	0.0	0.0	0.0		0.0							
Risk and Timing	1.0	1.0	0.5	0.5	0.5	1.0								
Totals	5.5	3.5	1.0	3.0	1.0	5.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% of Possible	0.262	0.167	0.048	0.143	0.048	0.262	0.071	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.000	0.636	0.182	0.545	0.182	1.000	0.273	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0	0	1	5	1	0	2	1	1	1	1	1	1	1
	10	6	0	0	0	10	0	0	0	0	0	0	0	0
Criteria Weights	10	6	1	5	1	10	2							

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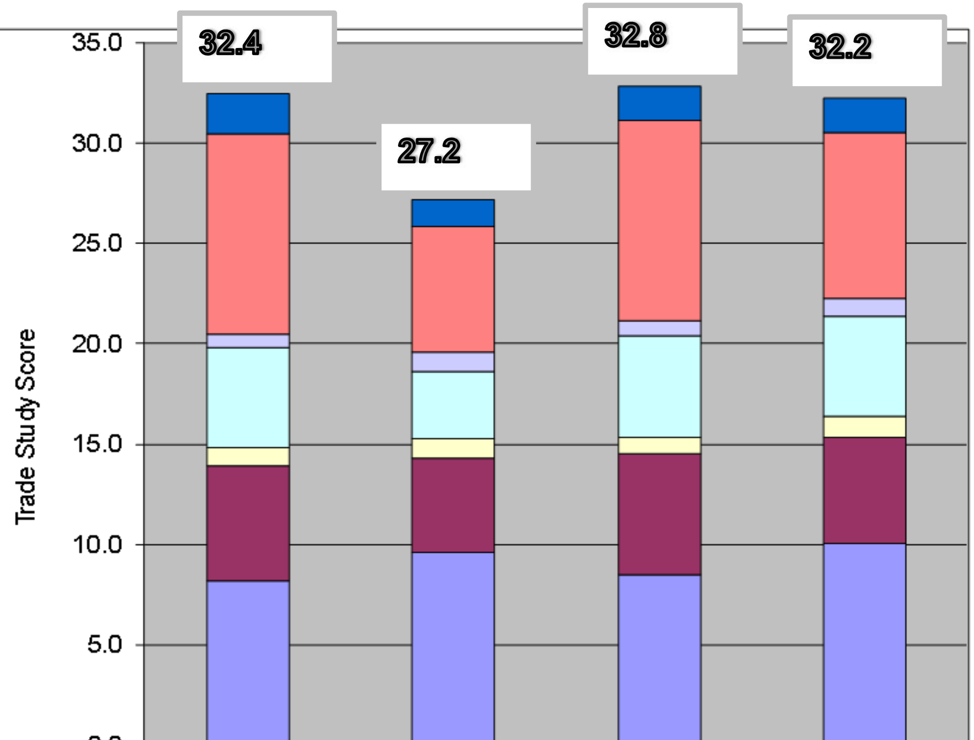
Accomplishments - Topology



	3-Phase PIM Baseline	Boosted DCDC + PIM	5-Phase	Dual Leg 3-Phase
Risk & Timing	2.0	1.3	1.7	1.7
Cost	10.0	6.3	10.0	8.3
Scaleability/Design Flexibility	0.7	1.0	0.8	0.9
Reliability	5.0	3.3	5.0	5.0
EMC	0.9	1.0	0.9	1.0
Packaging	5.8	4.6	6.0	5.3
Performance	8.2	9.6	8.5	10.0

Scoring was very close however the 5-Phase scored highest.

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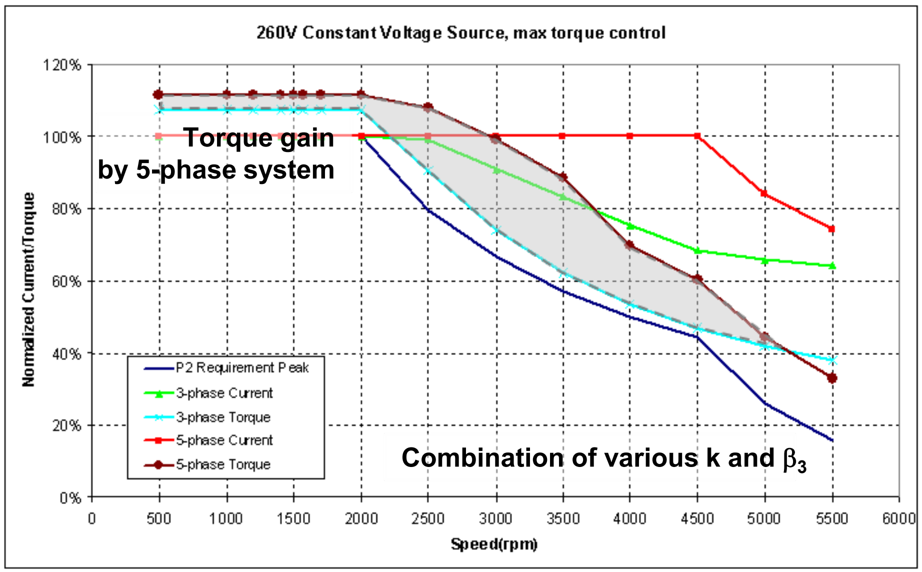
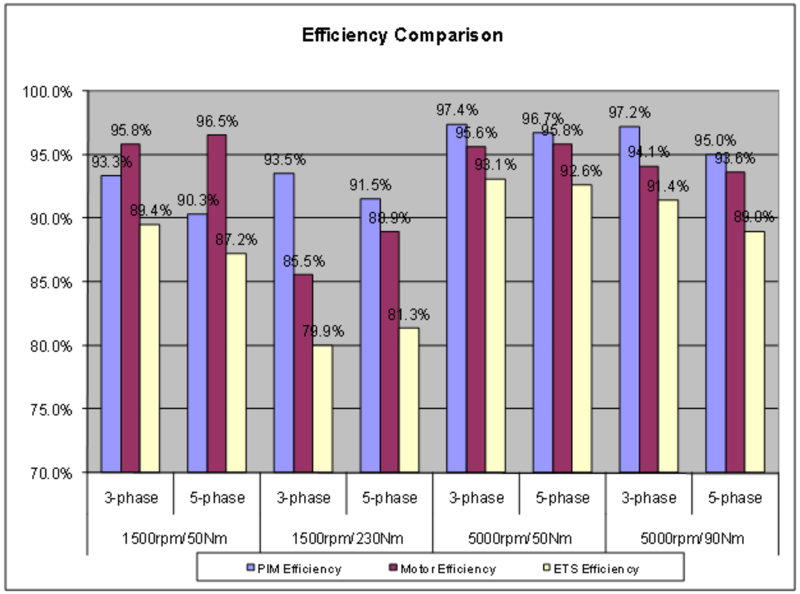
Accomplishments – 5-Phase vs. 3-Phase





		Three-phase	Five-phase
Number of Phase		3	5
Maximum Current	Arms	283	**168**
Switching Frequency	kHz	30	30
DC Capacitor	uF	300	**125**
Ripple Voltage	Vpp	7.47	**2.39**
	Vrms	1.47	**0.627**
PIM Input Current	App	23	30.3
	Arms	4.74	7.81
Cap Ripple Current	App	554.4	**387.9**
	Arms	159.4	**124.7**

5-Phase provides an increase in torque density and reduced DC bus ripple.

GM

FreedomCAR & Fuel Partnership

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Accomplishment - Multi-Phase Summary

1. **Multi-Phase machine can deliver more torque with same current than the baseline 3 Phase system.**
   - Multi-phase machine does not have 5th and 7th order torque ripple, which enables the machine design without skew. Therefore, it is possible to deliver more torque and less ripple with same current level.
2. **6-Phase concentric-winding IPM can deliver 12% more torque than the distributed-winding baseline system theoretically (assuming 16.5% of harmonic rotor flux density by PM).**
   - 9.8% comes from winding structure, and 2% comes from harmonic current injection
3. **5-Phase system can use same tools developed for 6-phase.**
   - 5-phase does not require additional power electronics for harmonic current generation. At the same time, it has to control harmonic current to maintain the control, and its optimal solution for entire speed range is not derived yet.
4. **5-Phase system delivers comparable performance in loss, and gives less stress on passive components.**
   - Multi-phase system can carry more switching loss due to increased number of switching per cycle. However, due to the distribution of PIM losses, thermal

The 5-phase topology shows intriguing possibilities.

Accomplishment - Components

- Developed two distinctive power module solutions
  - Advance silicon
    - Integrated temp and current sense
    - Chips solderable on both sides
  - Next generation of joint technology
  - Simplified interconnect technology
- Capacitor capable of meeting high temp environment using polypropylene film
  - Improve resin
  - Attachment of bus bar to capacitor
  - Matching capacitor to drive cycle
- Improved board technology for high temp environment using PWB technology

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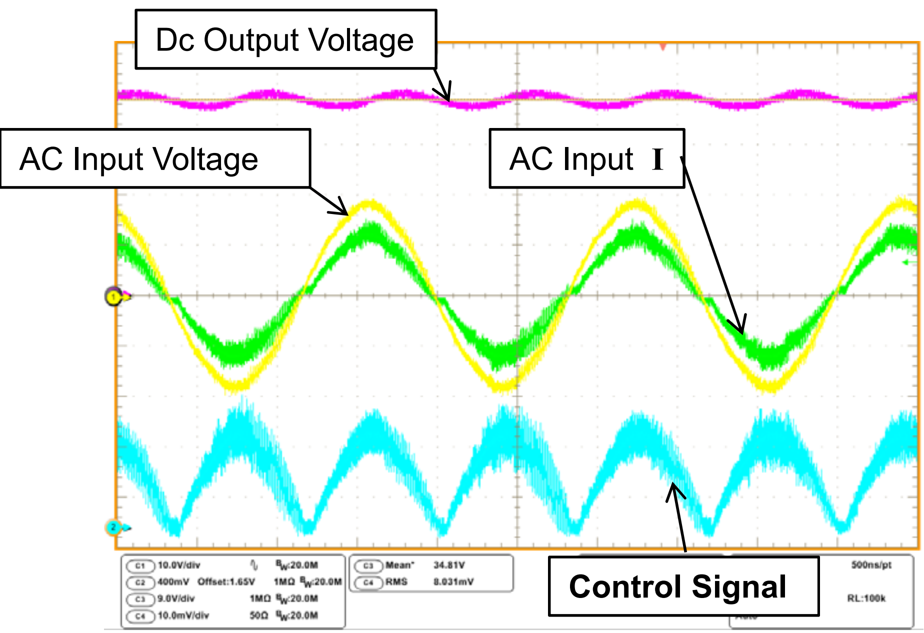
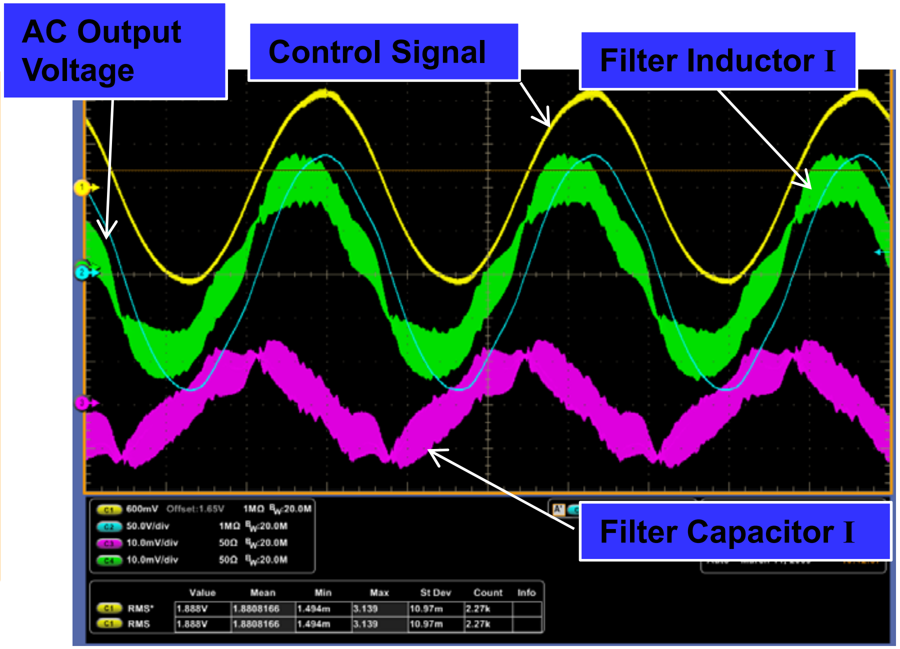
Accomplishment - Charger

- **Built breadboard hardware**
- **Performed simulations and verified control strategy**
  - **Charging and V2H**
- **Completed schematic**



Charger Function



V2H Function

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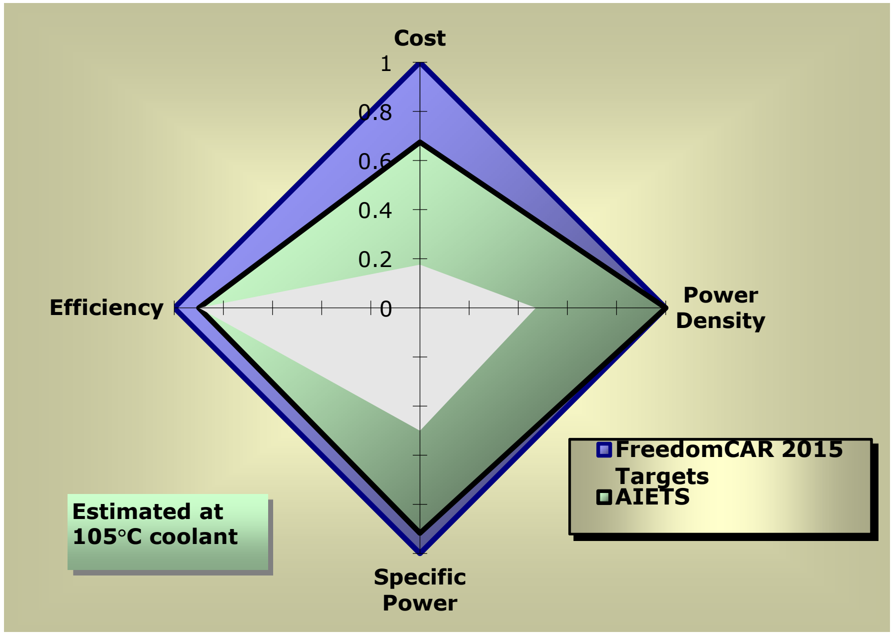
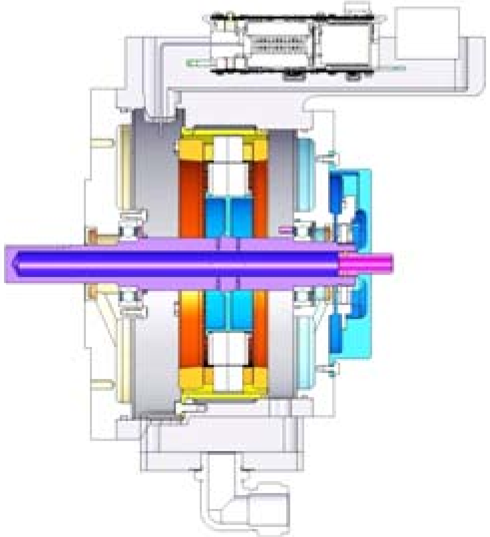
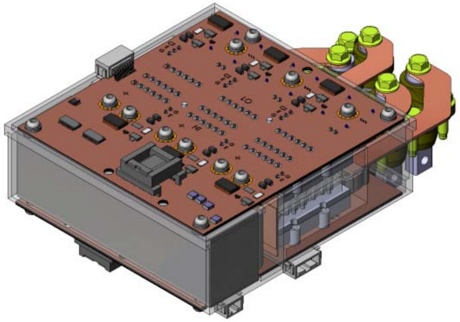
Accomplishments - Design

- **Technologies assessed : 29**
- **Configurations/Types: 36**
  - Topologies, bus, EMI filtering, components, and concepts

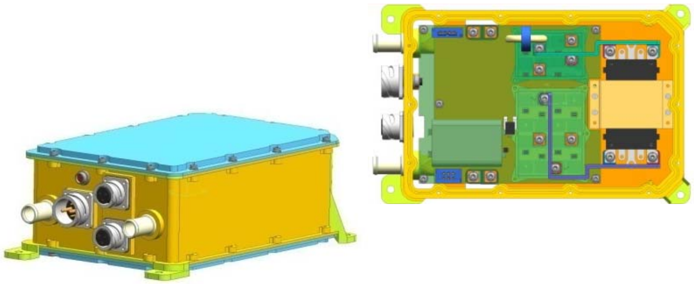




Integrated Motor and Inverter Concept



Inverter Concept



Charger Concept

Future Work

- **FY09**
  - Complete component testing
  - Finalize test plan for ETS
  - Finalize Design for AIETS
    - Preliminary Design Review
    - Critical Design Review
- **FY10**
  - Build AIETS prototypes
  - Begin characterization testing of AIETS
- **FY11**
  - Complete characterization testing of AIETS
  - Verification Tests with Government Lab

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Future Work – Characterization Testing

Hardware Usage	Inverter	Motor	Fixture
Electrical Verification			
Test Asset #1 Bench Testing	1		
Test Asset #2 Dyne Testing (Thermocoupled)	1	1	Test Housing
Test Asset #3 EMC Radiated & Conducted	1	1	Test Housing
Temp/Vibe Characterization and Margining			
Test Asset #4 Step Stress	1		
Test Asset #5 (Thermocouple)	1		
Test Asset #6 Vibe Survey	1		
Test Asset #7 Sine Sweep Resonance Survey	1	Eliminated for more component testing	
Environmental Seal Evaluation Test Asset #8			
Durability Test Assets #9-12 (System Verification)			
DOE Lab Test	1	1	Test Housing
Spare	2	1	

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Technical Targets - AIETS Hardware

Requirement	*Target*	*Comply*	*Technology to Address Requirements*
Continuous power output (kW)	30	Yes	Current systems have capability
Peak power output for 18 seconds (kW)	55	Yes	Current systems have capability
Operating voltage (V dc)	200 to 400; nominal 325	Yes	Current systems have capability
Maximum current (A dc)	300	Yes	Current systems have capability
Precharge time—0 to 200Vdc (sec)	2		Current systems have capability
Efficiency at 10 to 100% of maximum speed for 20% of rated torque (%)	> 90	Yes	Silicon carbide diodes, Motor Control
Maximum switching frequency (kHz)	20	Yes	Advanced processor and gate drive
Maximum fundamental electrical frequency (Hz)	1000	Yes	Current systems have capability
Ambient operating temperature (°C)	-40 to +140	Yes	Advanced Thermal.
Minimum isolation impedance-input terminals to ground (Mohm)	1	Yes	Current systems have capability
105C Coolant Temperature System			Advanced thermal, SiC diode, high temp. caps
Weight (kg)	≤ 52	Yes	Topology, advanced thermal, integrated bus structure, power module, and capacitor.
Volume (l)	≤ 21	Yes	Topology, advanced thermal, integrated bus structure, power module, and capacitor.
Unit cost for quantities of 100,000 ($)	≤ 1045	Yes	Part reduction, simplified construction, low cost motor , and commonality between applications

Summary

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

- Clearly identifying system requirements are key factor in program success
- Must understand factors that influence system performance and reflect into trade study criteria
  - Modes of operation in vehicle drive cycle
  - Environment
- Trade study shows that topology winners dependent on system operation strategy
- Hardware design needs to be flexible to address vehicle applications
  - PHEV, HEV, FCV, and EV
  - Power level
  - Environment

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