November 29, 2011

Final Report- Advanced Integrated Traction System

Period Covered: October 1, 2007 through August 31, 2011

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I. Executive Summary

The United States Department of Energy elaborates the compelling need for a commercialized competitively priced electric traction drive system to proliferate the acceptance of HEVs, PHEVs, and FCVs in the market. The desired end result is a technically and commercially verified integrated ETS (Electric Traction System) product design that can be manufactured and distributed through a broad network of competitive suppliers to all auto manufacturers. The objectives of this FCVT program are to develop advanced technologies for an integrated ETS capable of 55kW peak power for 18 seconds and 30kW of continuous power. Additionally, to accommodate a variety of automotive platforms the ETS design should be scalable to 120kW peak power for 18 seconds and 65kW of continuous power. The ETS (exclusive of the DC/DC Converter) 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 DC/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. The nominal operating system voltage is to be 325V, with consideration for higher voltages.

This project investigated a wide range of technologies, including ETS topologies, components, and interconnects. Each technology and its validity for automotive use were verified and then these technologies were integrated into a high temperature ETS design that would support a wide variety of applications (fuel cell, hybrids, electrics, and plug-ins). This ETS met all the DOE 2010 objectives of cost, weight, volume and efficiency, and the specific power and power density 2015 objectives. Additionally a bi-directional converter was developed that provides charging and electric power take-off which is the first step towards enabling a smart-grid application. GM under this work assessed 29 technologies; investigated 36 configurations/types power electronics and electric machines, filed 41 invention disclosures; and ensured technology compatibility with vehicle production.

Besides the development of a high temperature ETS the development of industrial suppliers took place because of this project. Suppliers of industrial power electronic components are numerous, but there are few that have traction drive knowledge. This makes it difficult to achieve component reliability, durability, and cost requirements necessary of high volume automotive production. The commercialization of electric traction systems for automotive industry requires a strong diverse supplier base. Developing this supplier base is dependent on a close working relationship between the OEM and supplier so that appropriate component requirements can be developed. GM has worked closely with suppliers to develop components for electric traction systems. Components that have been the focus of this project are power modules, capacitors, heavy copper boards, current sensors, and gate drive and controller chip sets. Working with suppliers, detailed component specifications have been developed. Current, voltage, and operation environment during the vehicle drive cycle were evaluated to develop higher resolution/accurate component specifications.

II. Discussion

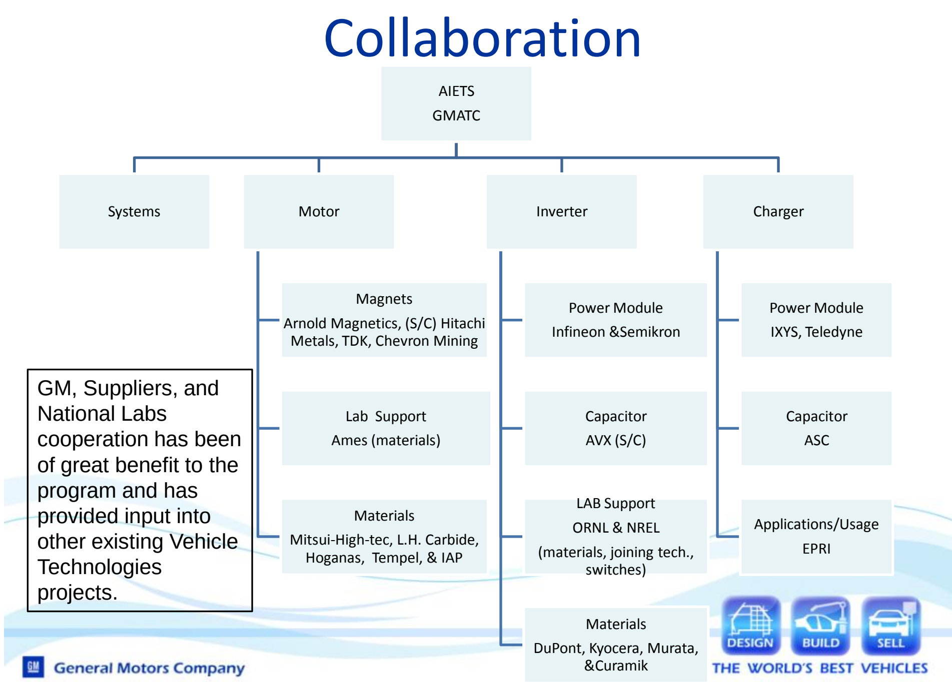
GM goal was to achieve all 2015 Technical Targets for the ETS as shown in the table below, but DOE's requirement was to meet the 2010 Technical Targets. Final results of the project were that all 2010 targets, and specific power and power density 2015 requirements at 105°C were met.

Technical Targets for Electric Propulsion System

	2010[a]	2015[b]	GM [b]
Cost, $/kW	<19	<12	<16
Specific power, kW/kg	>1.06	>1.2	>3
Power density, kW/L	>2.6	>3.5	>5
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>90%

a. Based on a maximum coolant temperature of 90°C
b. Based on a maximum coolant temperature of 105°C or air

This cooperative development project developed an Advanced Integrated Electric Traction System and a Bi Directional Converter. The National Energy Technology Laboratory (NETL) awarded GM a Cooperative Agreement on April 25, 2007. The project team is shown below. The project stared October 1, 2007 and was completed October 30, 2011. The project was divided into two phases.



III. Phase 1 (Experimentation/Study)

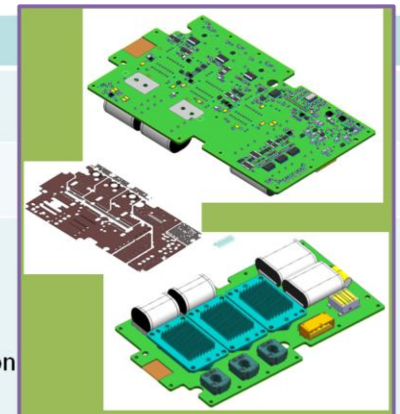
Phase 1 was to define component specifications, investigate technologies and topologies, and then select those that had potential for the range of automotive electric traction applications. The first phase was from October 1, 2007 through July 31, 2008 and was completed per plan. The range of sources for technologies and topologies were universities, national labs, suppliers, and internal GM R&D. Areas of component interest were thermal, power module, capacitor, gate drive, and control card. Thermal investigations were in pin fin heat sinks, indirect and direct jet impingement. Power module packaging types conventional, transfer and encapsulated were studied. Improved switches with on-chip current and temperature sense were studied. Capacitor PP (Polypropylene) and PET(Polyethylene Terephthalate) along with packaging options were evaluated. Gate Drive and Control Card high temperature circuit and components were evaluated. Topologies that were evaluated were 3-phase, Z-source, boost converter, multi-phase, dual leg 3-phase, and double ended. Technologies selected for ETS development were as follows:

1. Thermal, pin fin array copper and aluminum for performance and cost
2. Two types of conventional based power modules, one press-fit pin and the other with flex foil for low inductance and lower cost
3. On-chip current and temperature sense for lower system cost
4. PP capacitor package discretely for life and lower cost
5. Heavy copper board gate drive with bus structure for low inductance
6. Thermally isolated control card for life
7. Multi-phase topology was chosen for higher power density

IV. Phase 2 (Development/Demonstration)

Phase 2 was to design, build, and test the ETS was from August 1, 2008 through May 31, 2011 the December 2008 updated project plan. The ETS development was based on vehicle needs and learning's from Phase 1. The figure below shows the approach used by element and why.

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 adapt 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.

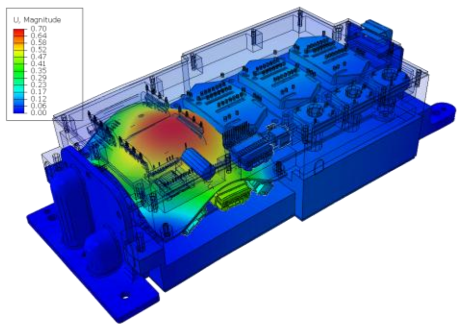


Heavy Layer Circuit Card Technology

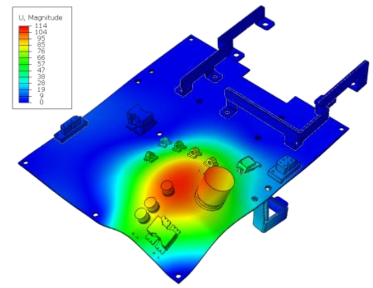
During the development adjustments were made in the project to align the ETS with a GFE (Global Front Wheeled Drive Electric) Hybrid. The GFE is a strong hybrid architecture that has a greater potential for impacting energy savings in the United States.

The design task generated multiple concepts to be considered. Each concept had electrical, mechanical stress, and thermal analysis, shown below, performed. Additionally manufacturing, reliability, and cost assessments were completed. Concepts that were viable were then assessed for scalability. In parallel, requirements for components were refined based on design analysis and experimentation. Requirement findings were provided back to each appropriate supplier for their use. This allowed for continued refinement and detailed component design to be completed and incorporated into ETS concept. A Preliminary Design Review was held in June ’09 and a Critical Design Review in September ’09.

Mechanical (Modal Analysis)

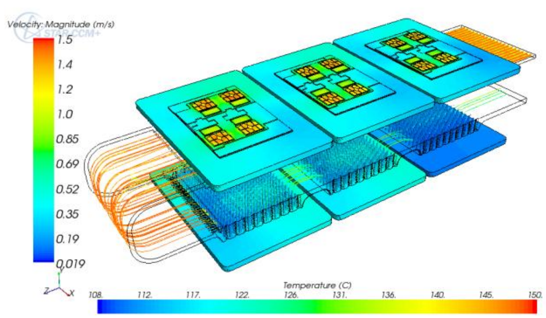


Inverter

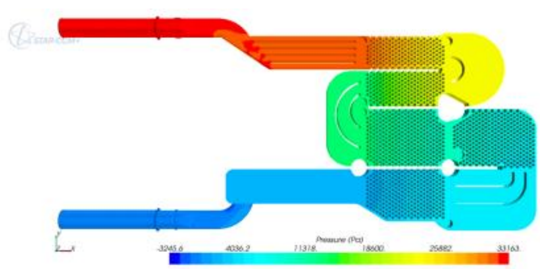


Bi-Directional Converter

Thermal Analysis



Power Module

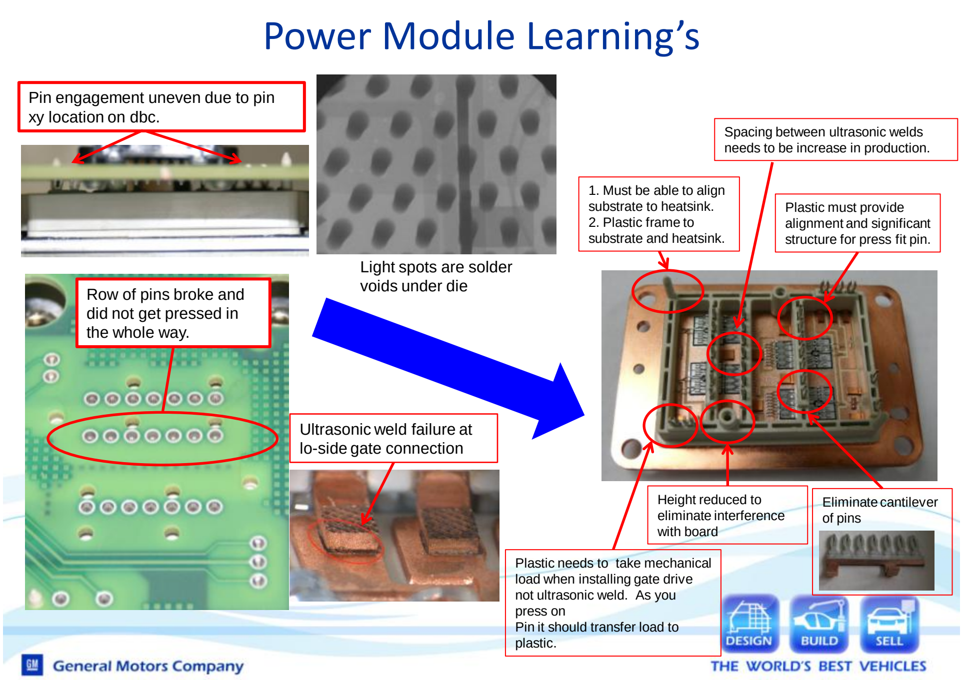


Bi-Directional Converter

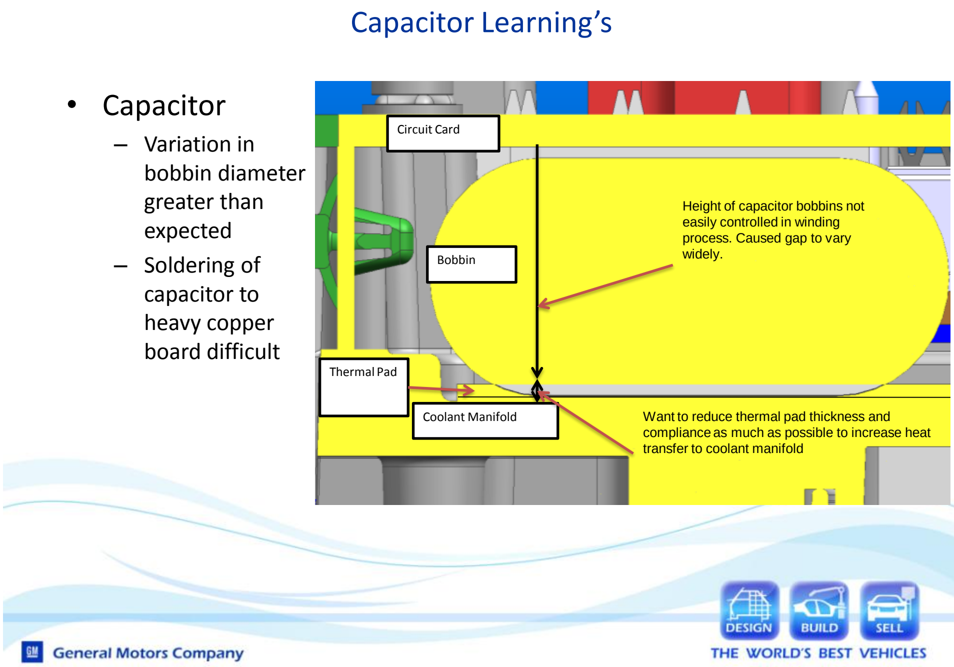
The build task started shortly after the Critical Design Review. Parts were placed on order. Key component parts (i.e. power modules, dc bus capacitor, heavy copper board) were received early in order to do mechanical fit checks and electrical bench testing before final parts were built. Breadboard units for the inverter and motor, and bi-directional converter were built using early parts for unit electrical testing in the last quarter of 2009. These early tests were designed to reduce project risk and improve unit performance. In February 2010 the first bar wound motor was built and in June 2010 the first inverter and bi-directional converter units were built and began electrical bench testing. ESS (Environmental Stress Screening) and dyne testing followed.

Testing was done individually and then finally as a system. This began the process of characterization of the units and the technology that it represents. The purpose was to identify and understand design and manufacturing issues excited by automotive environment and performance requirements. Tests that were performed were Electrical Bench, ESS, EMI, Dyne, and Vibration. Identified issues were root caused and verified. Considerable time and effort was needed to accomplish the testing and experimentation to identify and verify the root cause of failures. The following issues were identified on the inverter:

1. Power Module production inconsistencies: frame and pin alignment, ultrasonic welds, solder voiding, and press fit pin support during insertion.

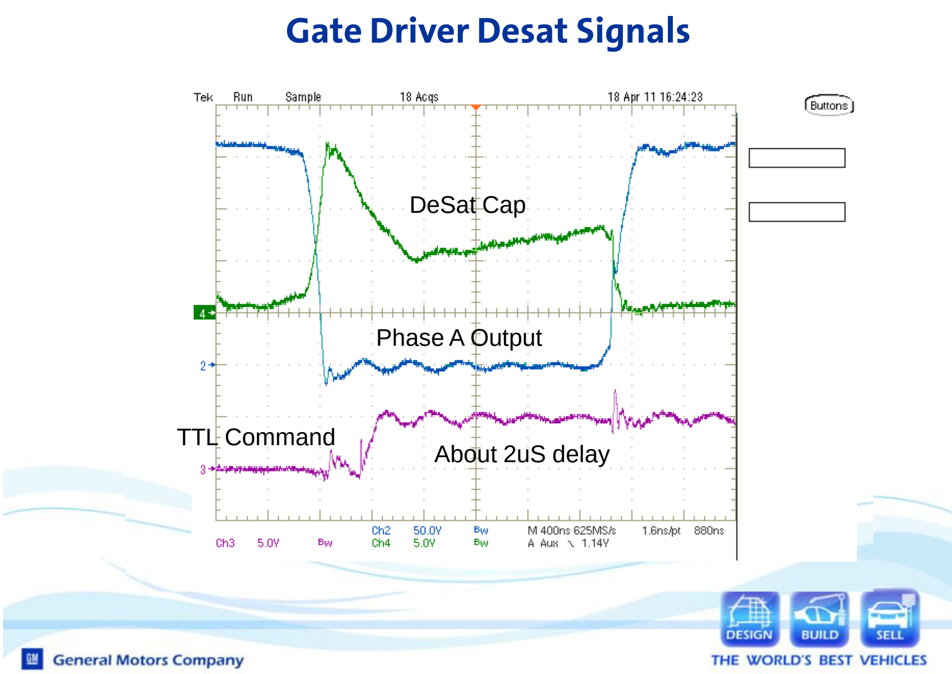


2. Capacitor variation of bobbin size, causing thermal interface issues to coolant.

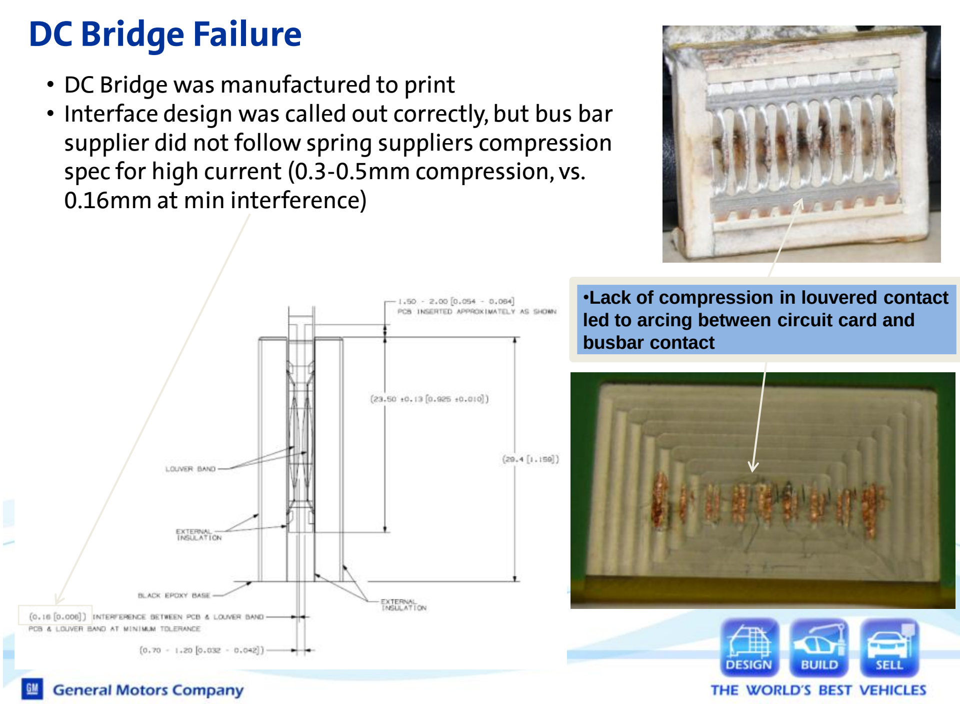


3. Heavy Copper Board device soldering, difficulty in consistence and quality of joint.

4. Gate drive IC and circuit, poor turn on and off and common ground plane.



5. DC Bridge bus bar, poor contact from lack of spring compression

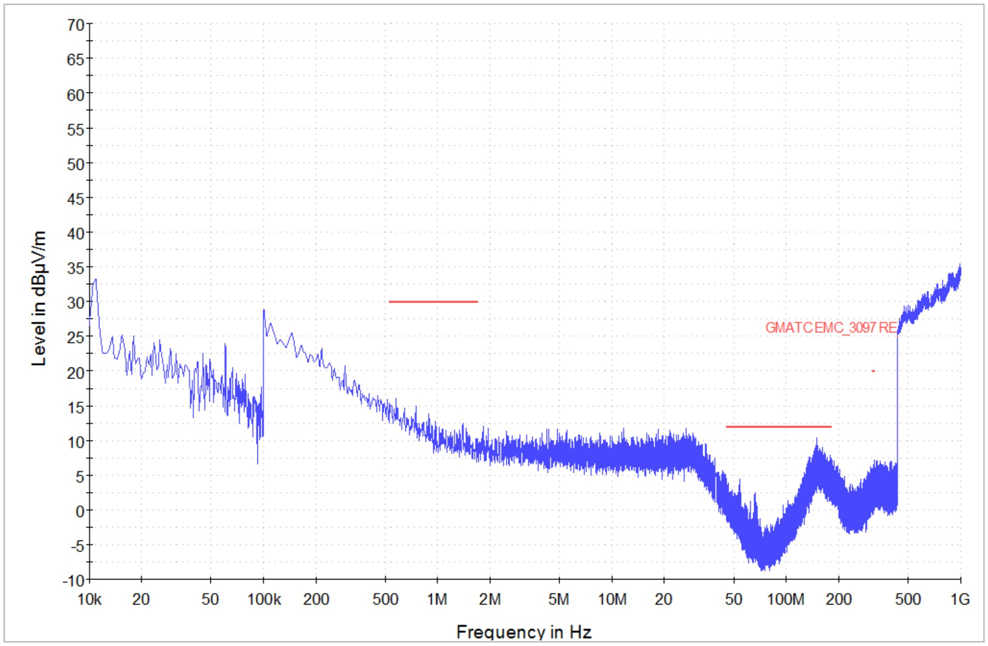


The bi-directional converter had power module failures caused by manufacturing defects requiring new process and quality standards to be implemented. The bar wound motor had significant manufacturing processes issues in coil forming and insertion, and coil welding. 5-Phase motor has a higher slot count and number of conductors than a conventional 3-Phase motor causing the increased complexity of the manufacturing processes. Additionally motor test data was correlated to simulation data and identified higher than expected leakage inductance. Through investigation, analysis and experimentation it was determined that longer than expected end turns accounted for the higher leakage inductance. If manufacturing processes can be improved allowing for a reduction in end turn length motor performance will be as originally predicted. All the identified issues have been communicated to suppliers and are being incorporated into the supplier's production design offering.

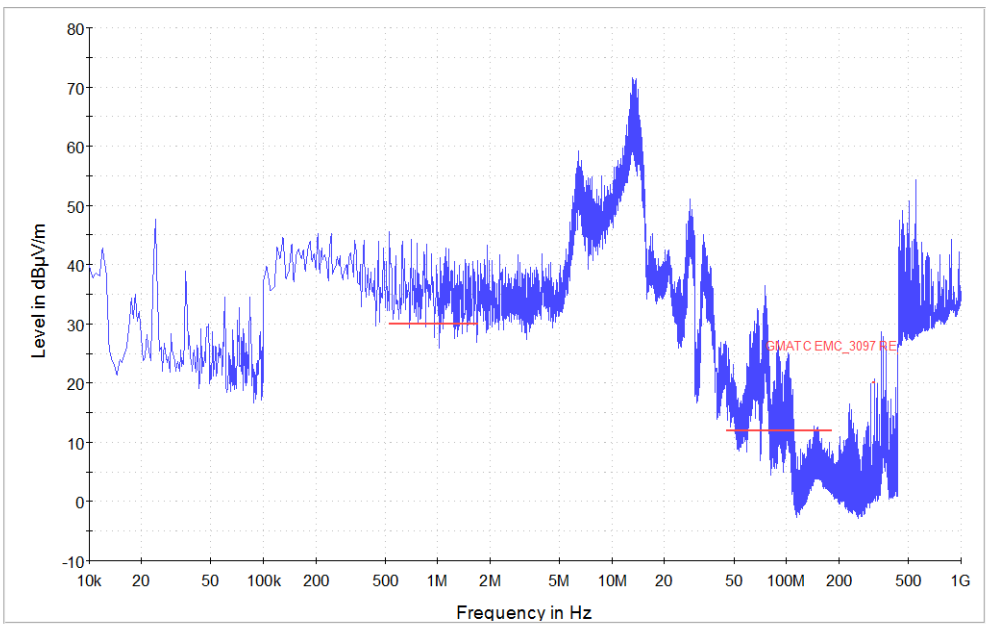
EMI testing was done in March '11. Tests that were performed were to determine the radiated and conducted emissions of the ETS. The following tests were performed:

1. RE GMW 3097 – AIETS in wakeup and drive modes
2. CE GMW 3097 – LISN on 12 V + and 12 V return lines
3. CE with current probe – Measure common mode current on all external cables

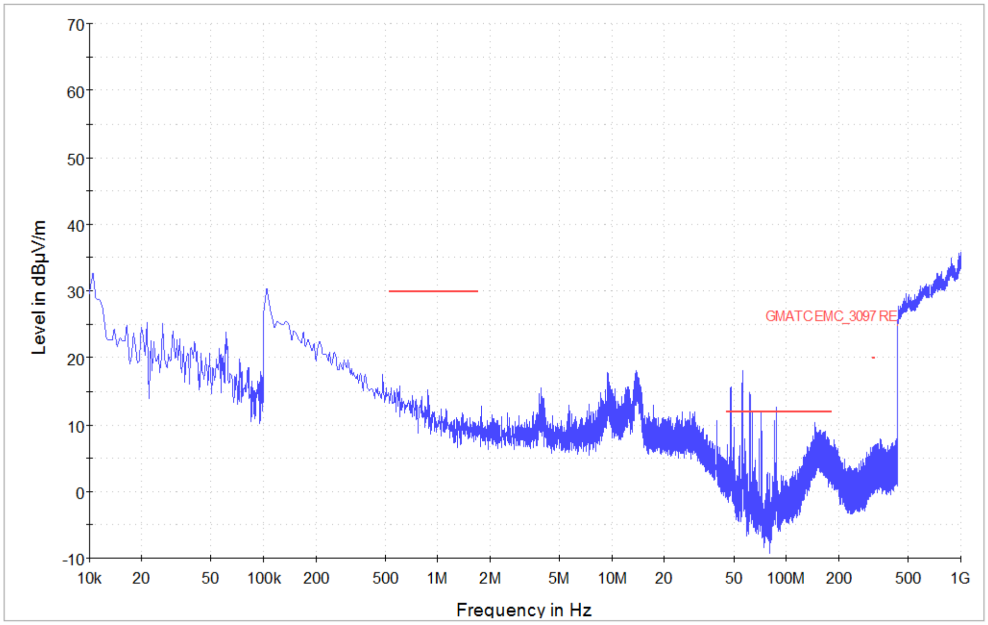
Results show, see below, that the ETS is not passing RE GMW3097, passing CE GMW3097, and CE with Current Probe shows IGBT switching noise being conducted on each external cable and through the output driveshaft. Reduction in EMI emissions was determined could be accomplished through a re-layout of the Bia's supply to meet GM EMI requirements.



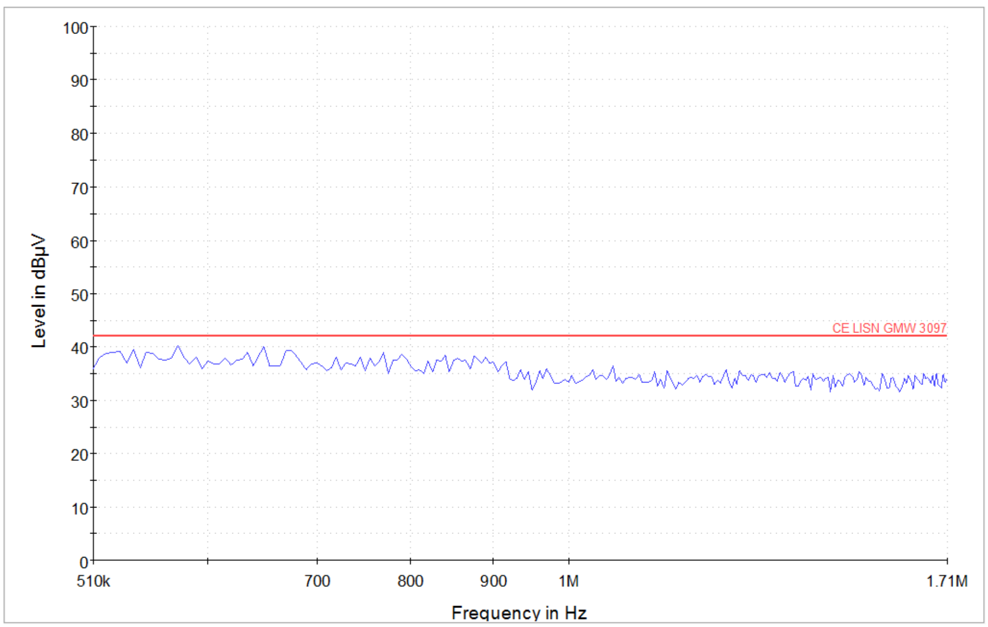
RE DOE 5-PHASE AIETS
CHAMBER AMBIENT
07MAR11



RE DOE 5-PHASE AIETS
300 HVDC & 12V - ENABLED
DRIVE MODE-ENABLED; 1KRPM
08MAR11

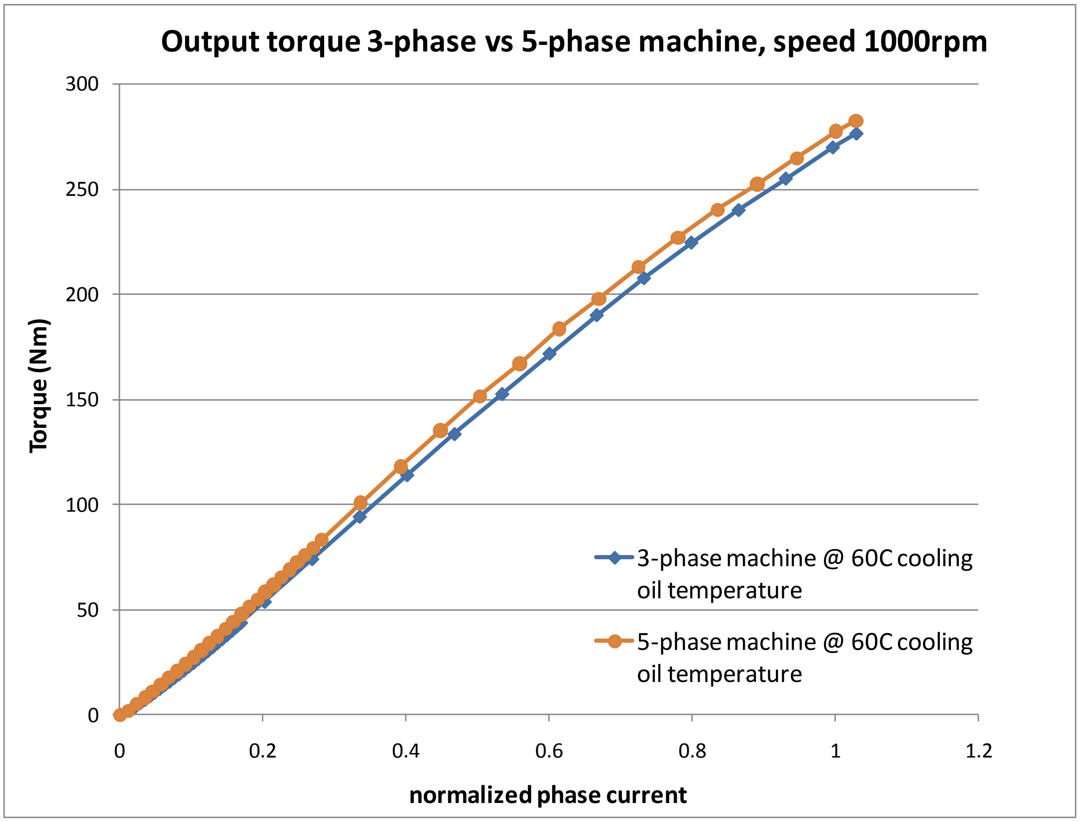


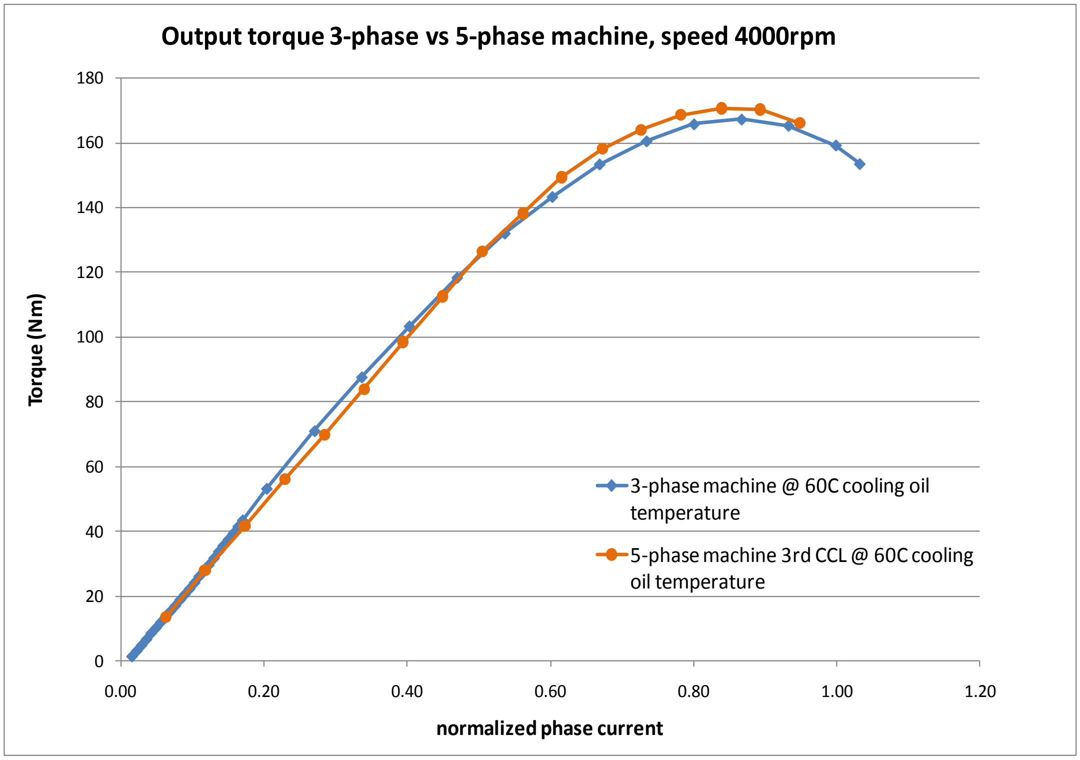
RE DOE 5-PHASE AIETS
300 HVDC - ENABLED
SIGNAL HARNESS CONNECTED
07MAR11

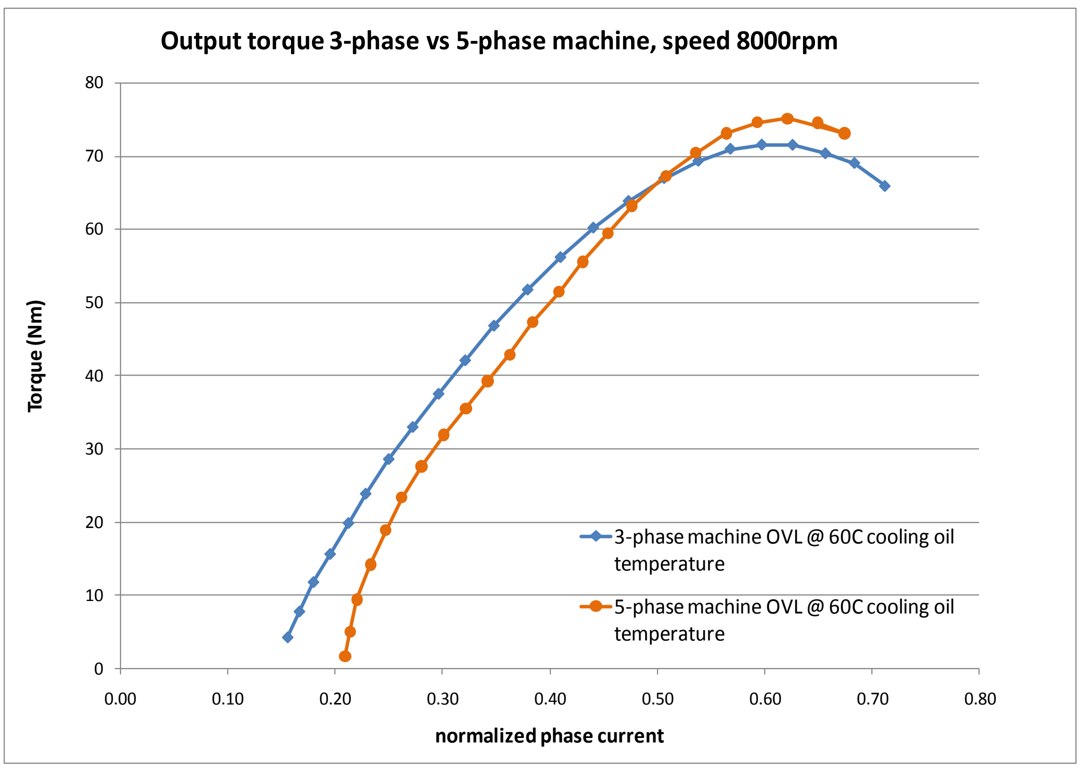


CE LISN B+ DOE 5-PHASE AIETS
300 HVDC & 12V - ENABLED
DRIVE MODE-ENABLED; 1KRPM
08MAR11

The integration of the motor and inverter into an ETS was done in March 2011. Dyne testing up to this point on the traction system was done with the motor and inverter not integrated so full instrumentation could be used. System efficiency, continuous and peak power, and hot and cold testing was done. Measured data from dyne tests are shown below and where verified during government witness testing in May 2011.




Output torque 3-phase vs 5-phase machine, speed 4000rpm
Torque (Nm)
normalized phase current
3-phase machine @ 60C cooling oil temperature
5-phase machine 3rd CCL @ 60C cooling oil temperature


Output torque 3-phase vs 5-phase machine, speed 8000rpm
Torque (Nm)
normalized phase current
3-phase machine OVL @ 60C cooling oil temperature
5-phase machine OVL @ 60C cooling oil temperature

ETS performance testing correlated to predicted performance from simulation when taking into account the motor high leakage inductance. Test data from 5-Phase machine shows higher peak torque/power than 3-phase machine, in particular in the field-weakening region, but the gain of the tested 5-phase machine is not significant because of the leakage inductance. Efficiency measurements showed that the 3-Phase machine was higher than the 5-Phase machine, however, 5-Phase has again the potential to match or have higher machine efficiency than 3-Phase if leakage inductance is reduced. Leakage inductance can be reduced by decreasing the motor end turn length by improving current manufacturing processes which is achievable.

This project developed an ETS that met DOE 2010 targets and met specific power and power density 2015 requirements at 105°C. Challenges in the areas of cost and system efficiency remain daunting to meet all the 2015 DOE targets. Cost reduction will require greater specific application component development to be done. Higher efficiency will greatly depend on improvement in motor winding production processes and the development of new switch technology.

<u>Publications</u>

- Program Kickoff October 30, 2007
- PEEM FY’08 Kickoff November 6, 2007
- 2008 Merit Review February 27, 2008
- AIETS Phase 1 Review July 17, 2008
- PEEM FY’09 Kickoff November 18, 2008
- 2009 Merit Review May 22, 2009
- PEEM FY’10 Kickoff October 27, 2009
- 2010 Merit Review June 10, 2010
- PEEM FY’11 Kickoff November 17, 2010

- 2011 Merit Review May 11, 2011

Intellectual Property

	RECORD OF INVENTION TITLE
1	Dual Leg Inverter Drive System with Anti-polarity Phase Connections
2	Sensor Mount Assemblies and Sensor Assemblies
3	Hermetic plastic overmolding of substrate
4	Method of Fast Approximation of Peak Summed Fundamental and Third Harmonic Voltages in Multi-Phase Electric Machine Inverter
5	Control Algorithm for 2 machines with 1 inverter
6	Boost inverter with 2 machines
7	Plastic lead frame with distributed-force substrate support
8	Direct IGBT Die Y-Capacitors to Control Electromagnetic Compatibility
9	Over-modulation Strategy for 5-phase Machine
10	Low Inductance Busbar Assembly
11	Methods, Systems and Apparatus For Controlling Third Harmonic Voltage When Operating A Multi-Phase Machine in an Overmodulation Region
12	Compensation Strategy for Bidirectional Matrix Converter Nonlinearities
13	Adaptive Compensation Startegy for Bidirectional Matrix Converter Nonlinearities
14	Methods, Systems and Apparatus for Adjusting Duty Cycle of Pulse Width Modulated (PWM) Waveforms
15	Method to Enhance THD and PFC in Single Phase ac/dc Boost Converter
16	Soft Start-Up for High Power AC – DC Charger/Inverter
17	Bidirectional Matrix Converter Battery Charger Control Strategy
18	Surface Enhancement Utilizing Boundary Layers with Indirect Jet Impingement
19	Crossed, overlapped power module bus structure
20	Electrical System for Pulse-Width Modulated Control of a Power Inverter Using Phase-Shifted Carrier Signals and Related Operating Methods
21	Fractional slot multiphase machines with open slots allow preformed/combined coils insertion from inner diameter, weldings reduction, decrease weldings failure, eliminate weld-end twisting/bending steps, eliminate costly/complex twisting/bending tooling a
22	Inverter Gate Drive PCB Inner Core High Current Access
23	Electromagnetic Interference Filter for Automotive Electrical Systems
24	Power Module Assemblies with Staggered Coolant Channels
25	Systems and Methods for Deactivating A Matrix Converter
26	Hairpin winding configuration for fractional slot multiphase machines
27	PWM strategy to minimize DC-link current ripple
28	Three Modes PWM Control Strategy for AC/DC Matrix Converter
29	Systems and Methods for Bi-Directional Energy Delivery with Galvanic Isolation
30	A DC Bus Capacitor of an Electrical Converter System
31	Maximum Voltage usage for Multiphase Machines in Field-weakening region
32	Integrated, High Performance, Low Inductance Power Inverter Module
33	Battery Pack Filter to Control Electromagnetic Compatibility

34	BIOS Extensions to Control Multiple Motors with Single-Motor Application Code
35	PWM Voltage Compensation
36	Fractional slot multiphase machines with open slots for simplified conductor insertion in a bar wound stator
37	Non-unity Power Factor Bidirectional Matrix Converter Charging Control Startegy
38	Forced Current Commutation Techniques in Isolated Current Fed Matrix Converters
39	Method to Improve Duty Cycles Calculation in the Over-Modulation Region
40	Synchronouos Current Regulator for 5-phase Machine with One Faulted Phase
41	Groove heat sink to improve power semiconductor module reliability