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Next Generation Inverter

Final Scientific/Technical Report

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General Motors LLC

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1 Executive Summary

The goal of this Cooperative Agreement was the development of a Next Generation Inverter for General Motors' electrified vehicles, including battery electric vehicles, range extended electric vehicles, plug-in hybrid electric vehicles and hybrid electric vehicles. The inverter is a critical electronics component that converts battery power (DC) to and from the electric power for the motor (AC).

Specifically, the objectives of Next Generation Inverter project were:

- Development of the technologies and the engineering product design of a low cost highly efficient next generation power inverter capable of 55kW peak/30kW continuous power.
- The team sought an inverter with improves cost of the power electronics to $3.30/kW produced in quantities of 100,000 units, and power density to 13.4kW/l, and a specific power of 14.1kW/kg to meet the DOE 2020 goals

The final design and prototype Next Generation Inverter achieved these objectives (see Figure 1).

	SPIM1	SPIM2	NGI Lo/Hi	TPIM1	TPIM2	TPIM3
# of 3ph bridges	1	1	1	2	2	2
kVA/L	14.6	21.8	31.4 / 43.5	34.6	23.7	26.8
kVA/kg	14.6	32.4	24.4 / 33.7	25.5	26.7	23.9

Note
- DOE's 2020 targets for a 55 kW single inverter are 13.4kW/L and 14.1kW/kg.
- Dual inverters have higher power density due to sharing of components between the two 3-phase bridges.

Figure 1 Inverter KVA Density Comparison[1]

The technologies developed in the Next Generation Inverter project will be furthered developed and targeted to be used in General Motors electrified vehicles in 2020 time frame.

[1] SPIM 1 and SPIM 2 are GM single inverters in production. TPIM1/2/3 are GM double inverters in production. NGI Lo is the actual Next Generation Prototype produced and tested. NGI Hi is the high power version of the Next Generation Inverter, which we did not produce in this project. Numbers for NGI Hi are based on analysis.

2 COMPARISON OF THE ACTUAL ACCOMPLISHMENTS WITH THE GOALS AND OBJECTIVES

Table 1 shows the Inverter Efficiency Target. Figure 2 and Figure 3 show the test result of the Next Generation Inverter prototype. Tests were conducted in GM dynamometer laboratory.

Table 1 Inverter Efficiency Target

Power Range (kW)	0-10	10-20	20-40	40-50	50-55
Efficiency (%)	>85	>96	>98	>94	>91

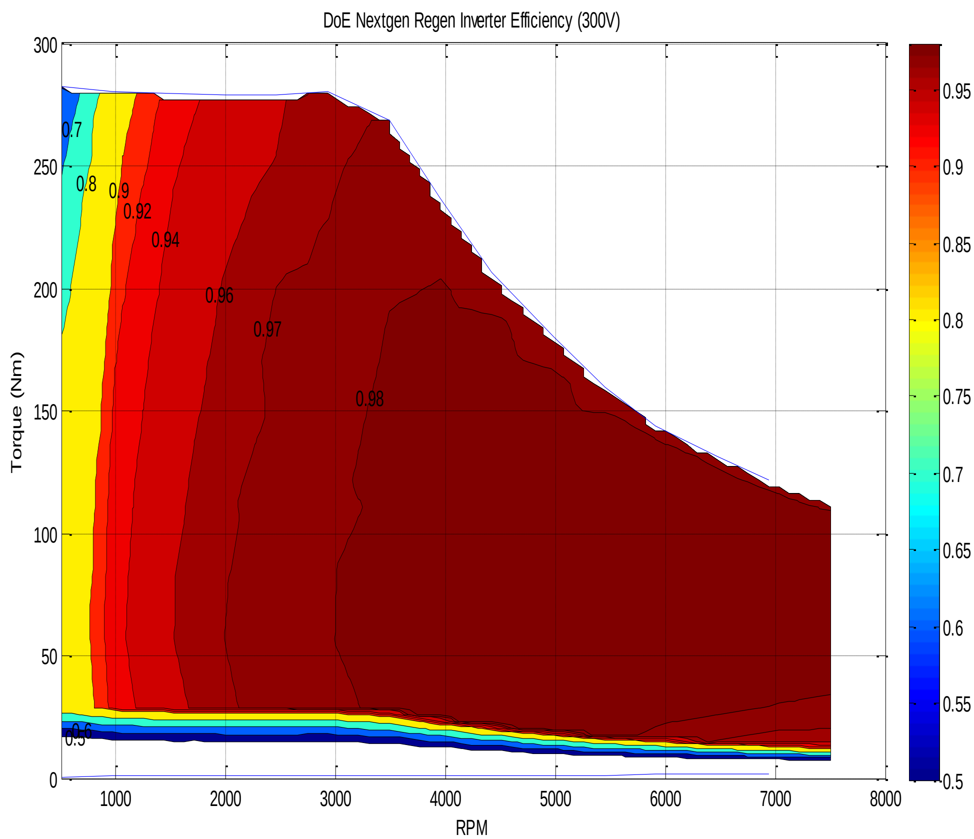

Figure 2 Next Generation Inverter Efficiency Map in Regeneration Mode (Tested with GM Production Motor)

Figure 3 Next Generation Inverter Efficiency Map in Motoring Mode (Tested with GM Production Motor)

Table 2 shows other performance requirements.

Table 2 Inverter Requirements: Goal vs. Accomplishment

Requirement	Target	Accomplishment[2]
Continuous power output (kW)	30	Exceed
Peak power output for 18 seconds (kW)	55	Exceed (based on analysis)
Weight (kg)	≤3.9	Not meet (due to higher power)
Volume (l)	≤4.1	Not meet (due to higher power)

[2] Based on test result unless otherwise noted.

Unit Cost for quantities of 100,000 ($)	≤182 *	Not meet (due to higher power)
Operating voltage (Vdc)	200 to 450; nominal: 325	Meet
Power factor of load	>0.8	n/a
Maximum current per phase (Arms)	400	Meet (upper limit of scalability, based on analysis)
Precharge time--0 to 200Vdc (sec)	2	Meet
Output current ripple –peak to peak (% of fundamental peak)	≤3	Meet
Maximum switching frequency (kHz)	20	Meet
Current loop bandwidth (kHz)	2	Meet
Maximum fundamental electrical frequency (Hz)	1000	Meet
Minimum isolation impedance-input and phase terminals to ground (Mohm)	1	Meet
Minimum motor input inductance (mH)	0.5	Meet
Ambient operating temperature (°C)	-40 to +140	Not tested
For Liquid Cooled Concepts		
Maximum cooling system flow rate (gpm)	2.5	Meet
Maximum inlet pressure (psi)	25	Not tested
Maximum inlet pressure drop (psi)	2	Not tested
Scalability (kW)	55-120	Meet (based on analysis)
Life (Years)	≥15	Not tested

3 Summary of Project Activities

The general approach of this project was for to solicit input from Tier 1, 2, and 3 suppliers to evaluate candidate technologies and prototypes, and to collaborate with National Laboratories to co-develop technologies aimed at reduced cost and increased efficiency without increasing volume or mass. GM then developed an inverter design aimed at ensuring modularity and scalability to meet all vehicle applications. The scalability requirement required that packaging would fit in all vehicle applications and possess the following additional characteristics:

- Consistent electrical parameters and mechanical structure
- Adherence to global manufacturing processes
- Provide adequate cooling for the capacitor
- Have low inductance

Following the development of a design meeting the above parameters, GM built multiple units were built and tested them over the complete automotive operating envelop.

3.1 Task 1: Project Management and Planning

No scientific/technical activities under this task.

3.2 Task 2: Technology Assessment

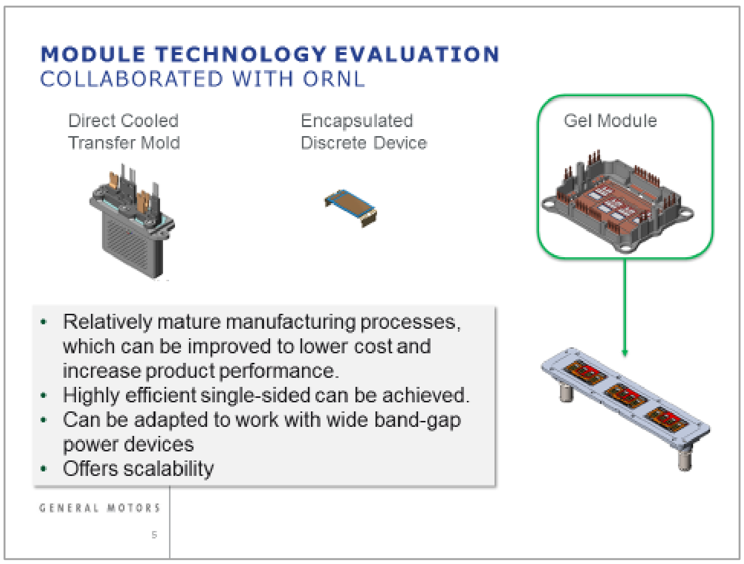

Figure 4 Power Module Technology Evaluation

Technology evaluation and testing was conducted in the first phase of this project, and concluded in FY13. Three types of power semiconductor packaging technologies, conventional (gel and lead frame), transfer molded and encapsulated were evaluated (Figure 4). While each technology offers its own path to achieve the performance and power density targets, the manufacturing processes for the module itself and the inverter architecture built around the module vary significantly. As stated in our approach, electrical and mechanical consistency and adhesion to global manufacturing processes are critical. Processes need to be mature enough and deployable globally by the time the inverter and key components manufacturing lines have to be built for the commencement of 2020 production.

We chose the conventional gel and lead frame construction for the inverter designed, built and tested (Task 3 thru 6), which was started in FY13.

The conventional gel and lead frame packaging has the following advantages

- Relatively mature manufacturing processes, which can be improved to lower cost and increase product performance.
- Highly efficient single-sided can be achieved.
- Can be adapted to work with wide band-gap power devices
- Scalability

Other technologies evaluated included film capacitor, wide bad-gap power semiconductor, power circuit interconnection and cooling mechanism.

3.3 TASK 3: TECHNOLOGY DEVELOPMENT

Our design was also guided by the following principles to achieve low cost and scalability

- Minimize material usage to lower BOM cost
- Scalable without significant additional tooling cost
- Manufacturing process can be developed for high volume production launch in 2020

Detailed design started in late FY13. GM designed the overall architecture of the inverter, power stage and control/gate drive board. Key components were designed with cooperation from sub-contractors.

The design features an integrated power stage concept (Figure 5)

- Closed aluminum coolant manifold
- Power semiconductors and substrates directly attached to coolant manifold
- Film capacitor built into coolant manifold frame, removing capacitor housing and providing better cooling
- Press-fit pins for signal and power circuit interconnection
- One piece lead frame for power semiconductor packaging
- One piece bus bar to route DC and AC current
- Gate drive and control circuit on one printed circuit board assembly (PCBA)

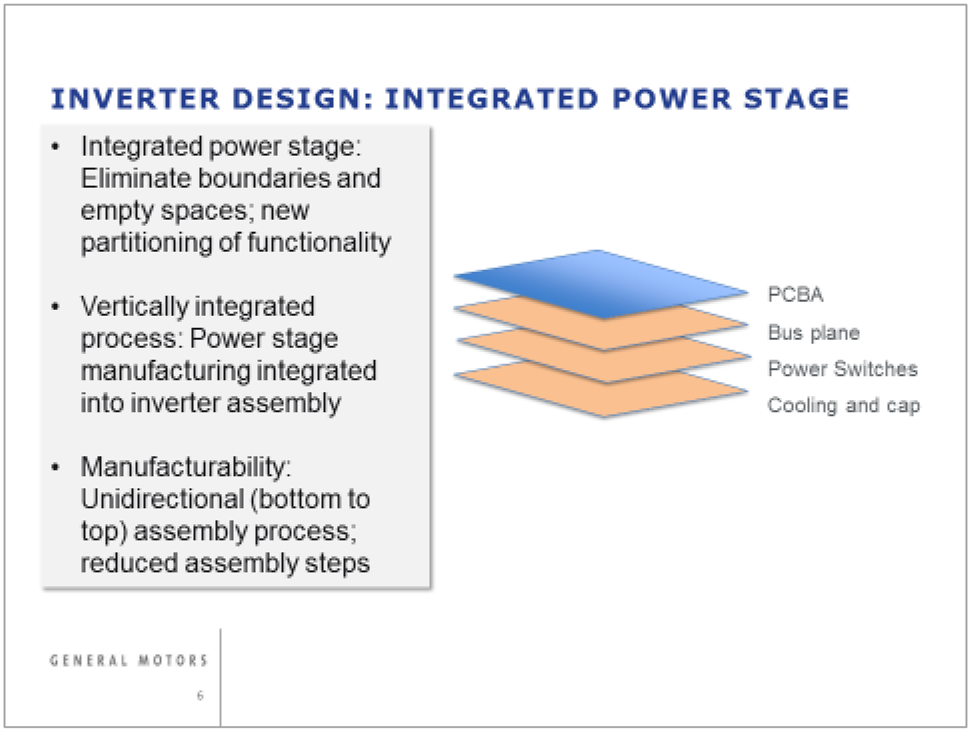

Figure 5 Integrated Power Stage

3.4 Task 4: Technology Build

The highly integrated nature of the design required a vertically integrated manufacturing process, which included

- PCBA process
- Power module process
- Film cap assembly process (portion)
- Electronics final assembly
- Final functional test

We chose to develop these processes mainly in GM's Kokomo electronics plant. Key processes we developed included die attach, DBC attach, wire bonding, encapsulation of dies and cap bobbins, press-fit pin and final assembly.

For die and DBC attach, we evaluated more than 20 configurations including different reflow technologies, lead-free solder material compositions and processing parameters. We assessed each solder techniques based on projected yield, thermal shock (-55^{o}C to 150^{o}C) results and attach quality (3D Xray, Cross-Sectioning). Condensation soldering was chosen for the final prototype build.

Five configurations was evaluated for encapsulation of dies and film capacitor bobbins. We conducted high temperature/high humidity tests on each configuration and made the final selection based on the test results.

In the Next Inverter Design, press-fit pins are used to connect

- Power stage lead frame to DC and AC bus bars
- Power stage lead frame to Control/Gate Drive board
- Film capacitor bobbins to DC bus bars

We collaborated with Interplex Industries Inc. to develop a proper press-fit pin for this design. Fixtures and operation parameters were developed in-house to press the bus bars and control/gate drive boards on to the lead frame. It is important to ensure the integrity of the components and solder joints on the PCB during this operation. Strain gauges were installed to monitor the deformation of the board during experimental operation. The keep-out areas were then optimized based on the result.

Figure 6 Press-Fit Pin Development

Figure 7 the inverter build process flow.

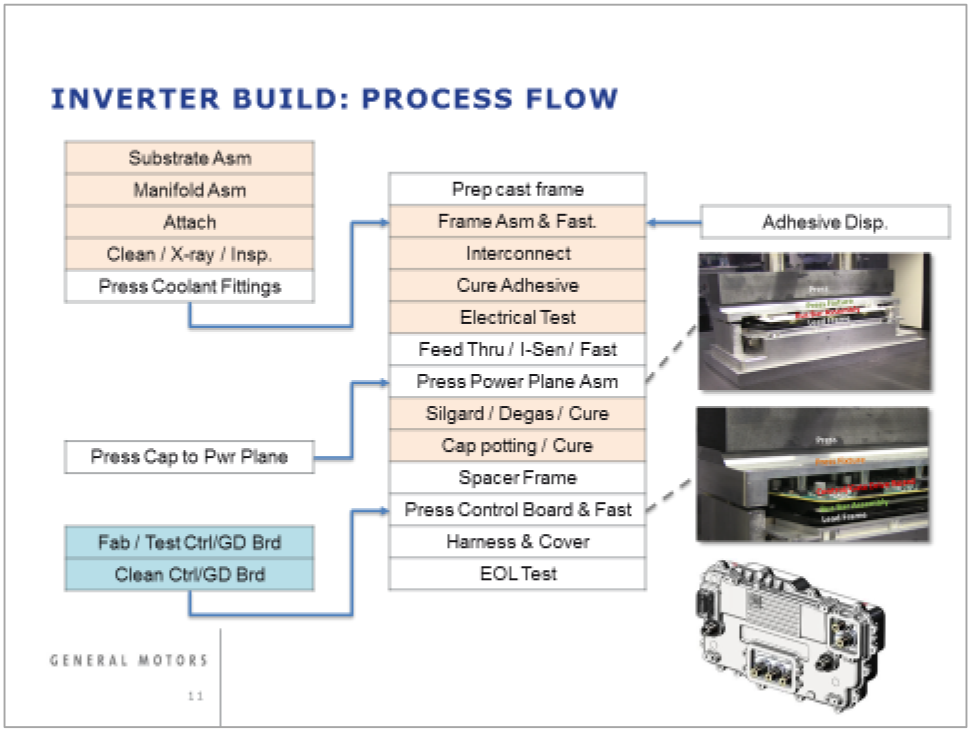

Figure 7 Inverter Build Process Flow

3.5 TASK 5: NON-DESTRUCTIVE CONFIRMATORY TESTING

All final prototypes went through inverter acceptance tests (Figure 8).

Figure 8 Inverter Acceptance Test

Performance of the final prototype was verified in GM's dynamometer lab.

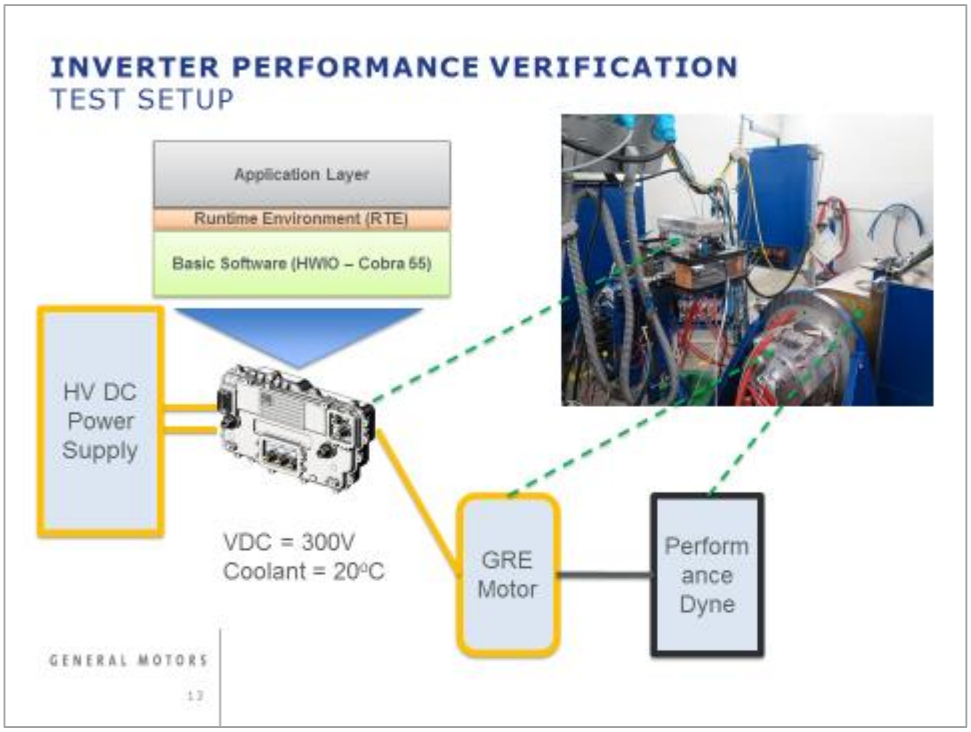

Figure 9 Inverter Performance Test Setup

Figure 2 and Figure 3 show the result of the performance tests.

Reliability tests (power cycle and intermittent operating life) revealed that this inverter still had some weaknesses.

We completed 9000 cycles. One IGBT within one of the power stages showed high Vcesat. Upon further examination, we determined that this IGBT had failed. Silicone gel above this

Figure 10 Close-up Picture of Failed IGBT after 9000 Cycles of IOL

IGBT showed disturbance (Figure 10), indicating that that was physical movement. X-Ray image of the die attach joint (Figure 11) shows evidence of high temperature reflow. One of the

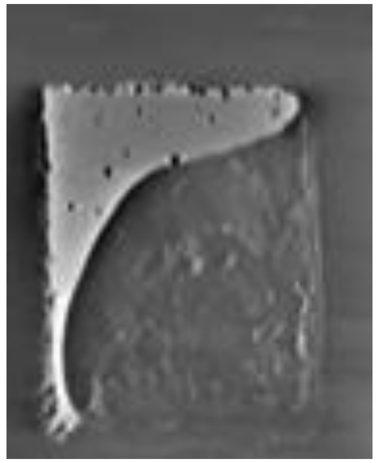

Figure 11 Xray Image of the Failed IGBT

potential root cause of the failure is solder fatigue. However, the other die attaches in this module do not show evidence of solder delamination.

We are still in process of understanding what caused the additional fatigue or possibility low solder quality.

In addition, we collaborated with the National Renewable Energy Laboratory (NREL) to study solder layer reliability. This study confirmed that the solder technique must be improved to make this inverter design to be more reliable.

3.6 TASK 6: PRODUCTION COST ASSESSMENT

Product cost study was conducted after the prototype build. We made the following assumptions

- Annual volume: 100K
  - 240 days/y; 417 units/d
  - Four years production, flat pricing
- Capital equipment and tooling
  - Dedicated capital equipment for power stage and finally assembly
  - Consumed capital for PCBAs
  - Standard cost of capital
- Direct labor hours based on line concept.
- Cost of operation based on fully filled factory with efficient operations.
- Industry standard yield, warranty cost, SG&A and EBIT; efficient and competitive market.
- Bill of Materials (BOM) – based on GM established cost targets; some actual quotes are still higher than targets.

In the BOM, we achieved significant reduction of "non-power-conversion" materials. Power semi cost is still the dominant factor in the BOM. Even higher volume will be needed to reduce PCBA cost.

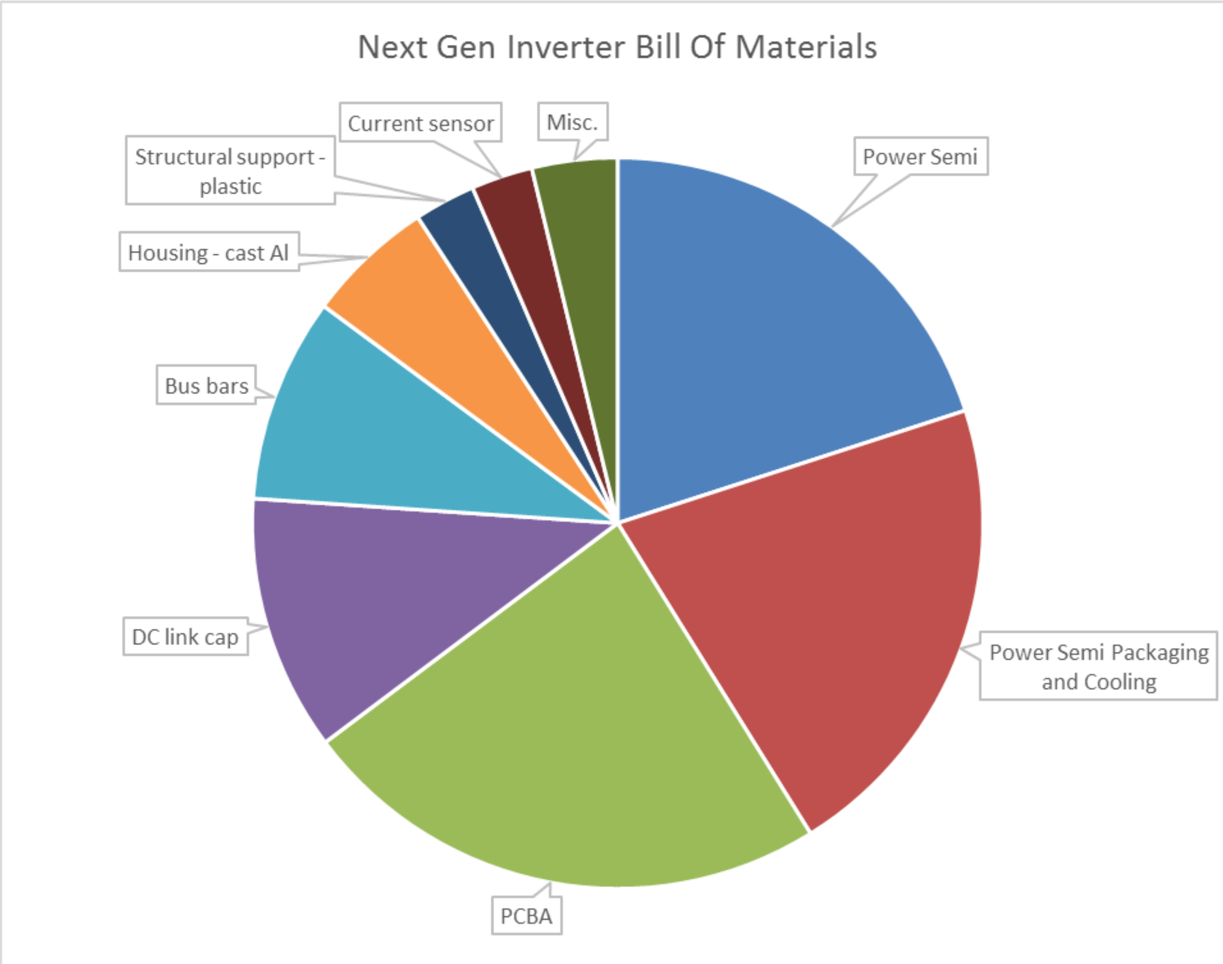

Figure 12 Next Generation Inverter BOM Cost Breakdown

The cost study was presented to DOE on August 18, 2015.

4 Products Developed under the Award

1. **Final prototype test assets:** 8 complete inverters and 7 integrated power stages. (Not including prototypes and test coupons to support process development.)

2. **Publications and Presentations**

- Zhao, Z. "Next Generation Inverter Project Wrap Up", Presentation in EETT meeting, Southfield, MI, February, 2016.
- Zhao, Z. " 2015 DOE Vehicle Technologies Annual Merit Review - Next Generation Inverter", Presentation in DOE Vehicle Technologies Annual Merit Review, Washington, DC, June 2015.

- Zhao, Z. “Next Generation Inverter”, Presentation in DOE Vehicle Technologies Program Kickoff, Oak Ridge, TN, November, 2014.
- Zhao, Z. "2014 DOE Vehicle Technologies Annual Merit Review - Next Generation Inverter", Presentation in DOE Vehicle Technologies Annual Merit Review, Washington, DC, June 2014.
- Smith, G. “Next Generation Inverter” Presentation in DOE Vehicle Technologies Program Kickoff, Oak Ridge, TN, November, 2013.
- Smith, G. "2013 DOE Vehicle Technologies Annual Merit Review - Next Generation Inverter", Presentation in DOE Vehicle Technologies Annual Merit Review, Washington, DC, June 2013.
- Smith, G. “Next Generation Inverter” Presentation in DOE Vehicle Technologies Program Kickoff, Oak Ridge, TN, November, 2012.
- Smith, G. "2012 DOE Vehicle Technologies Program Review - Next Generation Inverter", Presentation in DOE Vehicle Technologies Annual Merit Review, Washington, DC, June 2012.

3. Patents

- **US Patent Number US 9,295,184 B2:** Scalable and Modular Approach For Power Electronic Building Block Design in Automotive Applications