Electric Drive Technologies Roadmap Update

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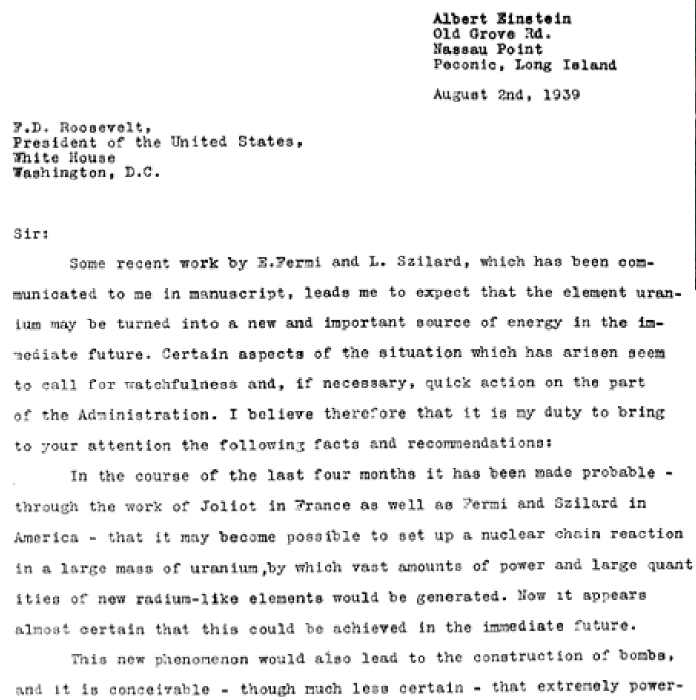

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely power-

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US DRIVE Partnership

- USCAR: United States Council for Automotive Research LLC – USCAR.org (Ford Motor Company, General Motors, and FCA US LLC)
- US Drive: United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability. A government-industry partnership.
  - U.S. Department of Energy;
  - USCAR, representing FCA US LLC, Ford Motor Company and General Motors;
  - 5 energy companies – BP America, Chevron Corporation, ExxonMobil Corporation, Phillips 66 Company, and Shell Oil Products US;
  - 2 utilities – Southern California Edison and Michigan-based DTE Energy;
  - the Electric Power Research Institute (EPRI)
  - Tesla and John Deere
- Electrical and Electronics Technology Team (EETT)

EETT Roadmap

- Latest roadmap is at https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf
- Published in June 2013 (search keywords: EETT roadmap)
- 2017 version is in the process

Current Trends

- Current trends in electric vehicle architectures and applications
  - OEMs are moving to skate board architectures for EVs
  - Vehicle application needs are expanding
  - PHEV ZEV range is increasing
  - Faster, high power charging is essential

=>Result: Higher vehicle voltages >600V

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Issues and Challenges

- Increasing costs:
  - current technologies are too expensive for mass market adoption
- Increasing power levels:
  - significantly higher power level systems are needed for heavier vehicle applications
- Limited space:
  - PHEVs need electric and IC propulsion systems packaged within the existing allocated vehicle propulsion space

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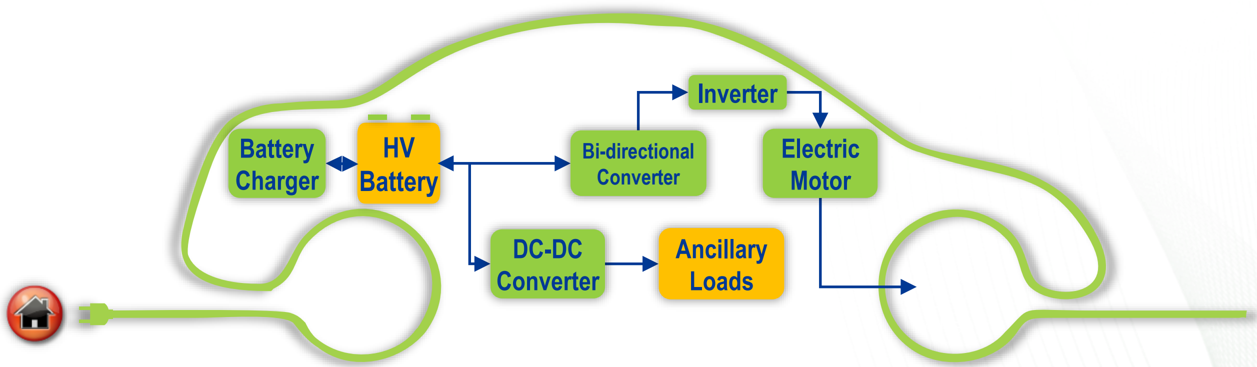
Electric Drive Technologies (EDT) Program

Traction Drive Systems

- **Power Electronics**
- **Electric Motors**



EDT Applications for Vehicle Traction Drive Span a Number of Functions

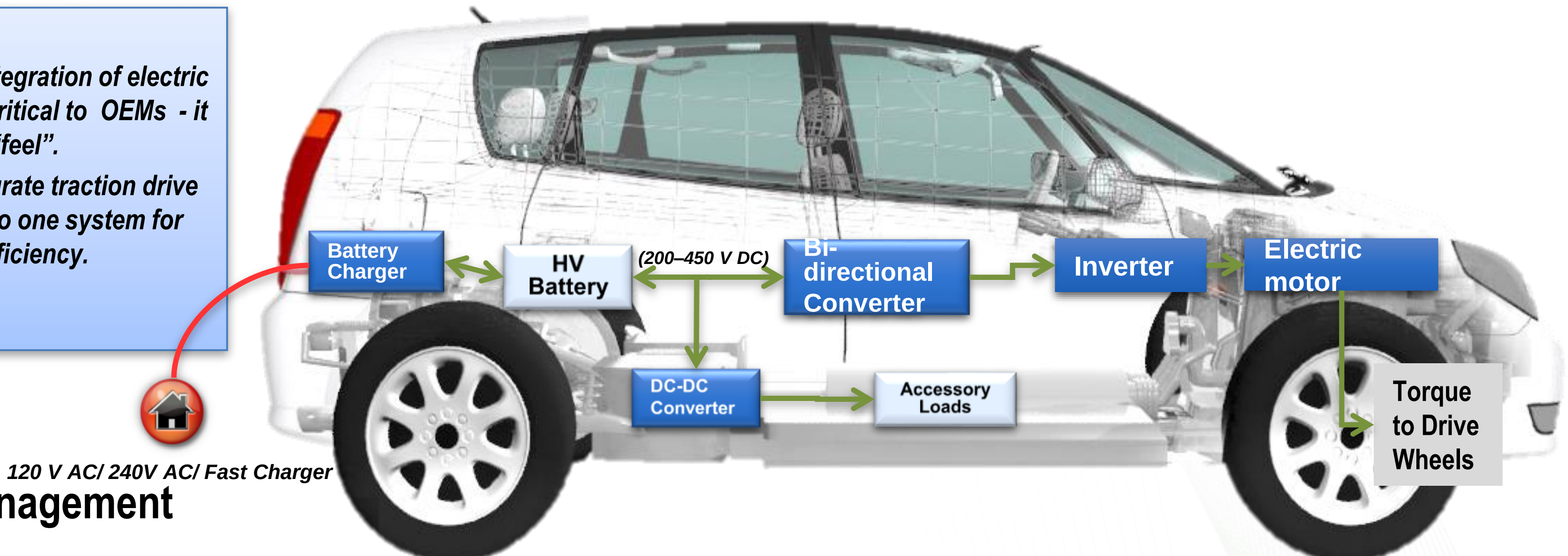
Traction Drive

- ***Battery charger*** – necessary for plug-in hybrids and electric vehicles
- ***Bi directional boost converter*** – steps up the battery voltage when the traction system requires a higher operating voltage than the battery can supply
- ***Inverter*** – converts direct current (dc) to alternating current (ac) for the electric motor
- ***Electric motor*** – converts electrical power to mechanical power for the wheels

Emphasis:

•Design and integration of electric traction drive critical to OEMs - it affects driving "feel".

•Goal is to integrate traction drive components into one system for greatest cost efficiency.



Power Management

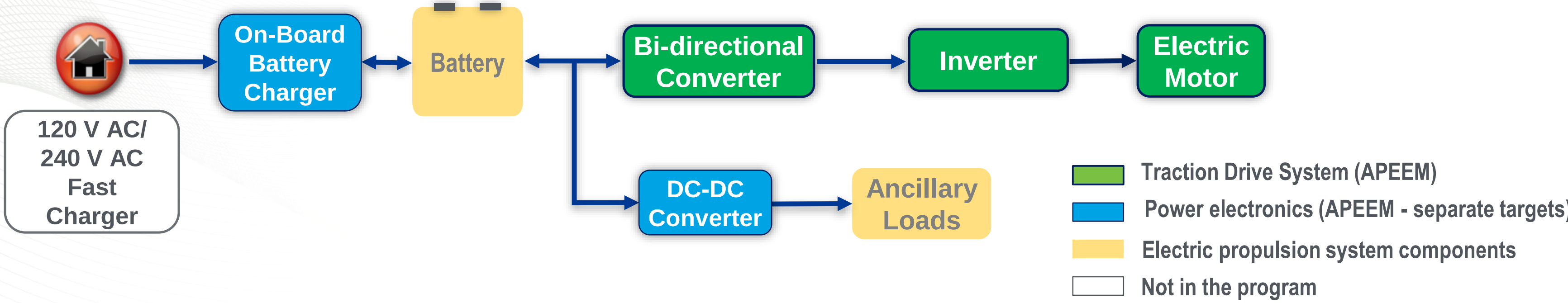
- ***Dc-dc converter*** – steps down the high battery voltage to power ancillary systems such as lighting, brake assist, and power steering, and accessories such as air conditioning and infotainment systems.

Electric Drive Technologies Research Program

Mission: Accelerate the innovation of electric drive technologies to enable a large market penetration of hybrid and electric vehicles

- Program targets and focus:
  - Increase performance (higher efficiency at higher power)
  - Reduce weight and volume (specific power and power density)
  - Increase reliability (15 year, 300K mile lifetime)
  - LOW COST

EDT Technical Targets



Traction Drive Systems (TDS)				
Impact	Reduce Cost	Reduce Weight	Reduce Volume	Reduce Energy Storage Requirements
Year	Cost ($/kW)	Specific Power (kW/kg)	Power Density (kW/l)	Efficiency (%)
2010*	19	1.06	2.6	>90
2015**	12	1.2	3.5	>93
2020	8	1.4	4.0	>94

Power Electronics (PE)		
($/kW)	(kW/kg)	(kW/l)
7.9	10.8	8.7
5	12	12
3.3	14.1	13.4

Electric Motors (EM)		
($/kW)	(kW/kg)	(kW/l)
11.1	1.2	3.7
7	1.3	5
4.7	1.6	5.7

Traction Drive System Requirements: 55 kW peak power for 18 sec; 30 kW continuous power; 15-year life

* **2010 traction drive system cost target met** with GM integrated traction drive system; 2015 weight and size targets were also met
** **2015 power electronics cost, power density, and specific power targets met** with Delphi advanced inverter with integrated controller

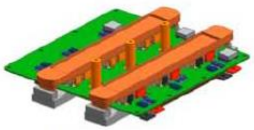
2025 GOAL: Reduce the production cost of power electronics and electric motors to $6/kW?

ORNL, NREL, and Delphi partner on technologies for 2016 Chevy Volt

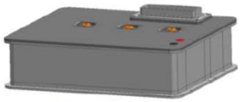
Advanced inverter to be produced domestically

- Developed improved packaging with SiC
  - 30% reduction in thermal resistance
  - 17% reduction in conduction losses
  - Lower cost through better semiconductor packaging and size optimization
- Technology used in Volt traction drive inverter
  - 6% improvement in city cycle efficiency
  - 10% increase in fuel economy
- ORNL conducted electrical characterization, modeling, and drive system simulation
- Research supported by DOE Vehicle Technologies Office

Discrete packaged Silicon unique to Delphi



Integrated PCB



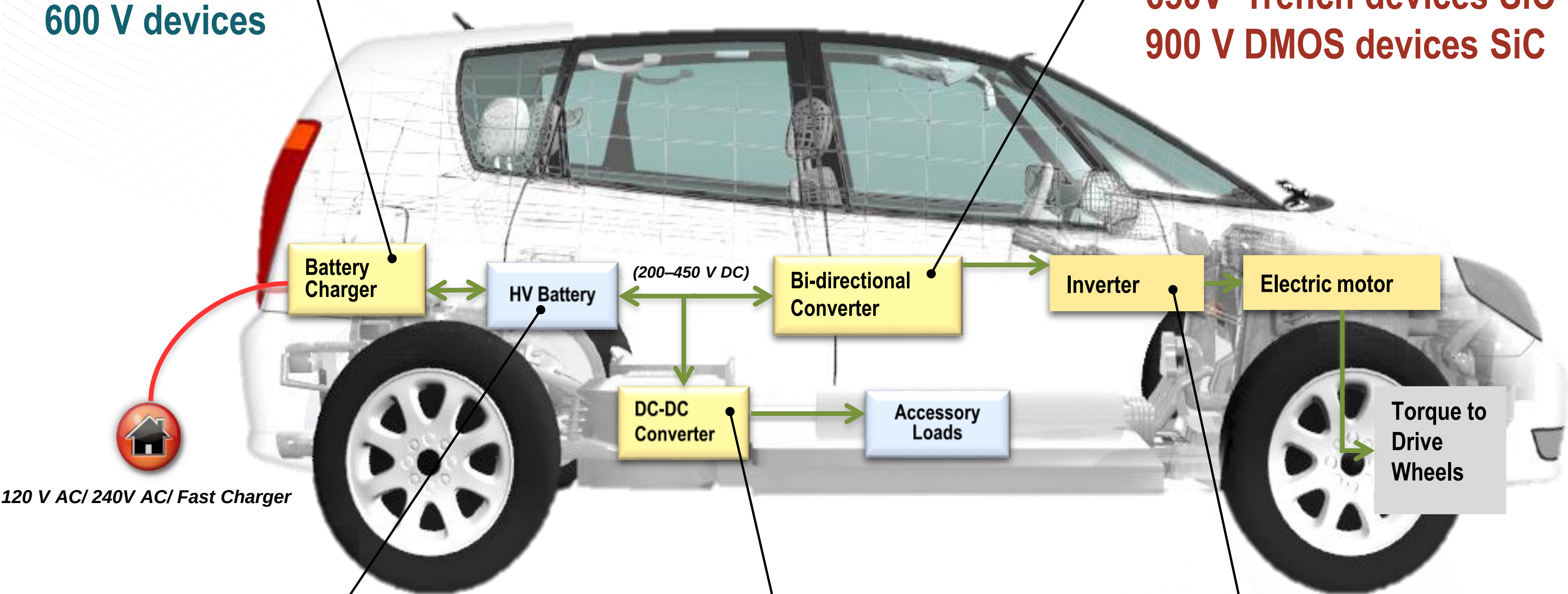
Advanced Inverter

2016 Chevy Volt

Projected Device Technology for Future

600 V devices- GaN
1200V DMOS devices SiC
1200V Trench devices SiC
650V Trench devices SiC
900 V DMOS devices SiC

650V Trench devices SiC
GaN technology
600 V devices



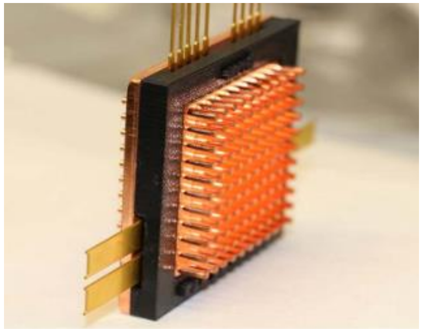
300 V, 600 V devices ?
GaN, Si
650V Trench devices SiC

600 V devices and
50V/ 100 V devices
GaN, Si
650V Trench devices SiC

600 V devices – w/o boost GaN
1000V devices- w boost SiC
900 V DMOS devices SiC
1200V Trench devices SiC

Power Electronics Research

Miniaturization of power electronics to enable wider vehicle applications while reducing cost

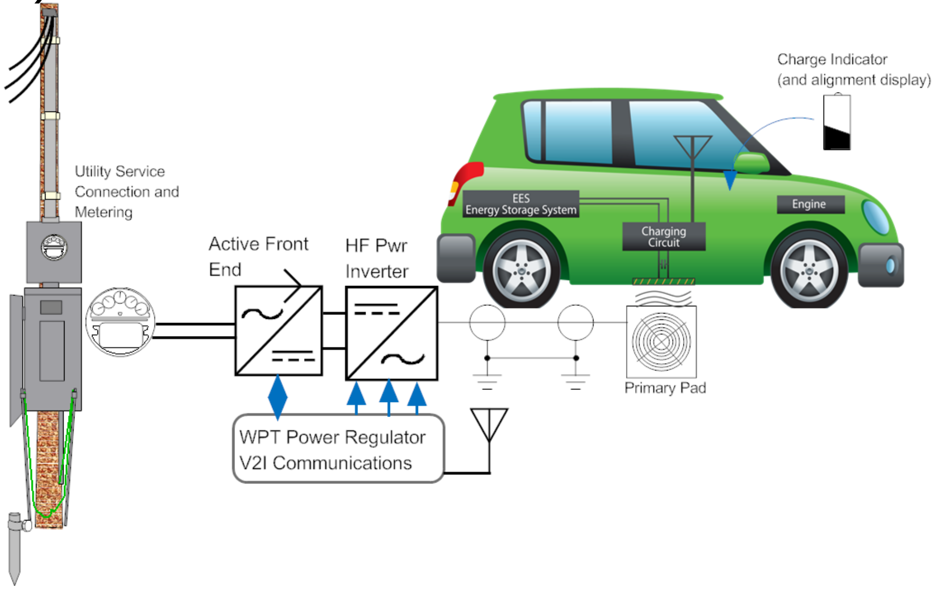


- Development of board based power electronics
  - Planar construction
  - Integration of bus structure, capacitor, and module substrate
  - Gate drives, power modules, and thermal systems
- Full utilization of emerging device capabilities
  - Decrease design margins and increase reliability
- Ultra conducting copper is a key enabler

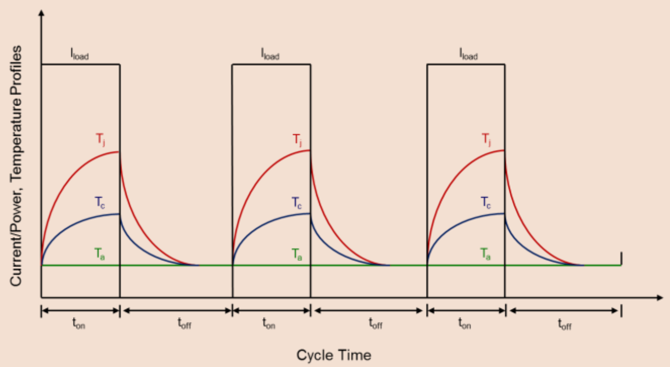
Result: One liter 100kW inverter at a cost of $270 by 2025?

High Power Charging

- Extreme Fast Charging: 350kW
- Wired
- Wireless
  - Convenience
  - Safety
  - Autonomous operation
  - Reduce vehicle battery size using dynamic on-road charging (or longer range)

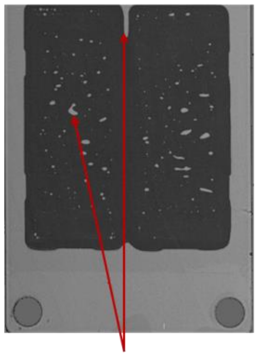


WBG Power Module Reliability



Si Test Standards: CENELEC; IEC 60747-34; JESD22-A122

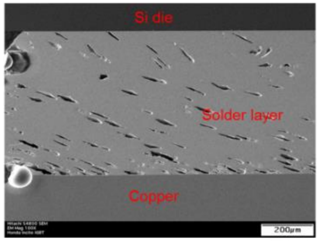
Bond layer image of substrate on base plate



Voids and cracks in solder layer

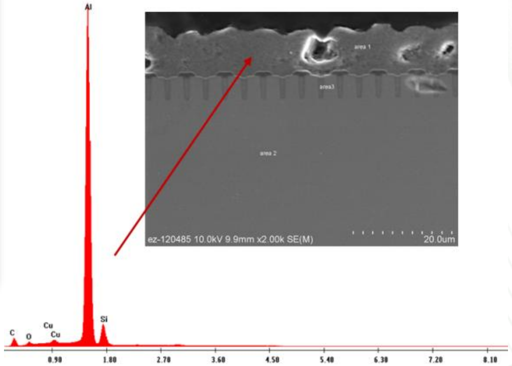
SAM (Scanning Acoustic Microscope)

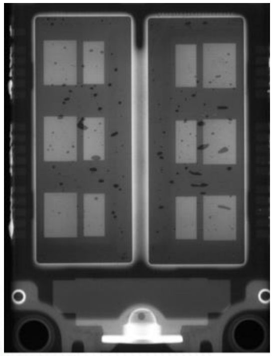
Cross-sectional side view of solder layer



Better resolution of voids in solder layer than SAM

SEM (Scanning Electron Microscope)





X-Ray Microscope

Images of voids in multiple stacked layers

Need for WBG Test Standards

- Different temperature requirements
- Bonded Interface issues with new materials
- Dynamic blocking voltage reliability
- Dynamic forward resistance and

  blocking resistance issues
- Reduced die area size and thickness

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Electric Motor Research

Reduce cost by utilizing fundamentally new materials

- Improved capabilities and performance
  - Heavy rare earth free and magnets
  - High efficiency low cost Si steel
  - Ultra conducting copper
  - Low cost, high voltage insulating materials.
- Application new materials in motor design innovations
  - Understand new material properties and how to use them to improve motor performance
    - 30 to 50% improvement in electrical and thermal conductivity
    - High performance computing for better analytical understanding, more accurate modeling, and optimization of motors

Result: Less than fourteen liter 100kW motor at a cost of $330 by 2025?

Trends Looking Towards 2025

- Move towards pure EV from Hybrid
  - 200 plus mile range
  - ≥ 60 kWh energy storage
  - Mass of vehicles > 3,500 lbs.
    - Vehicle structures mass being reduced, but greater energy storage being required
  - Propulsion power ≥ 150 kW
    - Meet reasonable acceleration performance
- Packaging
  - Running chassis – vehicle platform that allows multiple vehicle types to be produce
  - Integration into flat package

Trends Looking Towards 2025

- Transformation of Transportation “Mobility as a Service”
  - Autonomous EVs
  - 15 year/300K miles
  - Charging
    - Quick charge
    - Dynamic charge
    - Autonomous charge (wireless with auto docking)
  - Secondary impacts - Grid

Advanced Intelligent Power Module 2025?

Requirement	Current State-of-Art (WBG)	AIPM (Nominal)	(Scalability)
Peak power (kW)	30kW	100kW	200kW
Continuous power (kW)	15kW	55kW	110kW
Voltage Rating	900 to 1200V	900	1200
Max Device Current	100A	200A	200 A
Device Metallization			
Top	NO	NO	YES
Bottom	YES	YES	YES
Max Junction Temperature	180 C	250°C	250°C
Isolation	3 kV	3 kV	3 kV
Battery operating voltage (Vdc)		325(200-450)	
		650-700	Possible 800V
Switching Frequency Capability	30kHz	30-50kHz	30-50 kHz
Power factor		>0.6	>0.6
Maximum current (A)		600	800 ? (high torque, low speed? 600 is good
Precharge time--0 to 200Vdc (sec)		2	2
Eff (10-100% speed, 20% rated T curve) (%)		> 97 %	> 98
Torque ripple (%)		NA	
Output current ripple –peak to peak (%)	~5 ?	<= 5	? TBD
Input voltage & current ripple (%)	~5 ?	<= 5	? TBD
Current loop bandwidth (kHz)		2 kHz	2 kHz

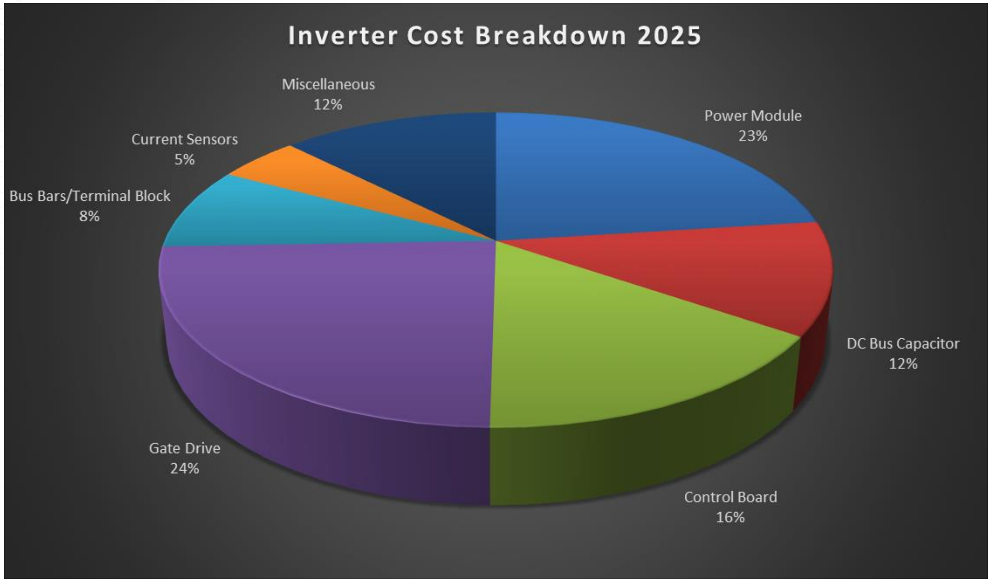
Requirement	Current State-of-Art (WBG)	AIPM (Nominal)	(Scalability)
Max fundamental electrical freq. (Hz)		2000 Hz	2000 Hz (Depends on the motor speed)
Ambient operating temperature (°C)		-40 to +125	-40 to +125
Storage temperature (°C)		-50 to +125	-40 to +125
Cooling system flow rate, max (ℓpm)	10	10	10
Maximum Partial Size for liquid cooled	1 mm	1 mm	1 mm
Maximum coolant inlet temp. (°C)	85	85	85
Maximum inlet pressure (psi)		25	25
Maximum Inlet pressure drop (psi)		2	2
Useful life (years/miles)	15/150,000	15/300,000	15/300,000
Minimum isolation impedance-terminal to grd (M ohm)		1	1
Minimum insulation impedance-terminal to grd (M ohm)		NA	
Min motor input inductance		0.5 mH	0.3 mH ?
Target Cost ($2.70/kW) @ 100K/Units	$732	$270	$540
Volume (100kW/ℓ)	5ℓ	1ℓ	2ℓ
Mass (16kW/kg)	6.25kg	2.00 kg	4.00 kg
*Note would like to reference appropriate documents from OEMs for testing requirements (i.e. GMW3172)			

EDT Power Electronics Cost Walk 2020 to 2025

Method

- Planar construction
- Integration of bus structure, capacitor, and module substrate
- Full utilization of SiC capability with high current device availability
- No external diode, use body diode of SiC MOSFET
- Integrated connection interface AC/DC
- Ultra conductive material
- Estimated impact of technology improvements
  - 30% reduction in gate drive cost
  - 65% reduction in controller circuit cost
  - SiC with 50% premium over Si devices and elimination of external diode
  - 55% reduction in current sense cost

EDT Power Electronics Cost Breakdown & Targets 2025



Inverter Total	$	287.18
Power Module	$	62.98
DC Bus Capacitor	$	40.80
Control Board	$	39.27
Gate Drive	$	64.02
Bus Bars/Terminal Block	$	27.23
Current Sensors	$	11.99
Miscellaneous	$	40.89

*Numbers are for a 105 kW Inverter

Annual Merit Review

- Hydrogen and Fuel Cells Program and the Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting
- June 5-9, 2017, Washington, DC
  http://www.annualmeritreview.energy.gov