HybriDrive® Propulsion System

Cleaner, smarter power for Medium & Heavy Duty Vehicles

“Mechanical, thermal and packaging challenges of high voltage, high power electronics for heavy duty propulsion and power management applications.”

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Drivers of Hybrids in Medium to Heavy Duty Vehicle Markets

- **Governmental Policies and Regulations**
  - Positive Environmental Impacts (lower emissions).

- **Green Image**
  - Social Conscience.

- **Payback**
  - *Payback is a function of*
    - Fuel Prices.
    - Acquisition Cost.
    - Fuel Economy (System Performance).

Fleet Operators prefer a < 5 Year Payback
Most Common Hybrid Architectures – series vs. parallel

Series Hybrid Drive Train
- Sized for full all-electric mobility
- No mechanical coupling of engine to road enables maximum control over engine operation
- Applicable for fuel cell or battery powered vehicles
- Ideal for urban Transit Buses

Parallel Hybrid Drive Train
- Sized for desired braking energy capture
- Engine still mechanically coupled to road; enables higher efficiency at highway speeds
- Scalable for a wide range of duty cycles
- Ideal for trucks

Architecture choice dependent on application, vocation and duty cycle
Major Design Requirements Differences between Automotive to Heavy Duty Vehicles

- **Manufacturing Volumes**
  - Low: Buses
  - High: Trucks, Automobiles

- **Life and Reliability Requirements**
  - Longer life and more operating hours
  - More aggressive duty cycle

Major Differences Have Significant Cost Impacts & Drive Very Distinct Design Philosophies
Major Design Requirements Differences between Automotive to Heavy Duty Vehicles (cont)

- **Environmental Requirements**
  - More Mounting Location Options
  - Higher Vibration Requirements
  - Tighter Sealing and Humidity Requirements
  - Direct Solar Exposure
  - Larger Temperature Variations

- **Power and Size Requirements**
  - Larger vehicle weight requires more power
  - Higher power means more current and more heat dissipation
  - Higher Voltage/Current/Heat drives Package Size
    - Connectors, Capacitors, Bus-bars, Switches, Cables, Energy Storage, etc
Life and Reliability Requirements

- **Automobiles**
  - 10 years
  - 125,000 miles
  - 6000 hours

- **Medium & Heavy Duty Trucks**
  - 12-15 years
  - 250,000 – 300,000 miles
  - 22,500 hours

- **Transit Buses**
  - 15+ years
  - 500,000 miles
  - 52,000 hours

Heavy Duty Vehicles Have Much Higher Hours of Operation per Service Life
Heavy Duty System Layouts vs. Automotive Layouts

**Automotive:**
- ESS and Control located in Passenger Compartment (Controlled Environment)
- Inverter and Transmission under hood

**Trucks and Buses:**
- Components not located in passenger compartments
- More location options (OEM dependent)
  - Frame Rails
  - Roof
  - Rear Cab
  - Engine Compartments
  - etc

Different Mounting Options Opens Environmental Design Aperture
Governing Performance Specifications and Power Levels

### Power & Torque Levels

<table>
<thead>
<tr>
<th>Torque Level</th>
<th>Performance Requirements</th>
<th>Environmental Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-65 kW</td>
<td>OEM Specific</td>
<td>OEM Specific</td>
</tr>
<tr>
<td>~250 Nm Crankshaft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-120 kW</td>
<td>OEM Specific</td>
<td>SAE J1455</td>
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<tr>
<td>800 Nm Crankshaft</td>
<td></td>
<td>ISO 16750</td>
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<tr>
<td>150-250 kW (motor)</td>
<td>OEM Specific</td>
<td>SAE J1455</td>
</tr>
<tr>
<td>150-250 kW (Gen)</td>
<td>Vocation &amp; Duty Cycle Specific</td>
<td>ISO 16750</td>
</tr>
<tr>
<td>6900 Nm DriveShaft</td>
<td>White Book (USA)</td>
<td></td>
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</tbody>
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Understanding Propulsion Torque & Power Requirements and Operational Duty Cycles are Key to a Robust & Viable Heavy Duty Solution
Packaging Cost Challenges for Heavy Duty Hybrid Power Electronics

Medium/Heavy Duty Commercial Vehicle Inverter
Relative Component Cost Breakdown

Pennies Still Count

With the Increase in Performance, Size, Duty Cycle, Life and Reliability Requirements, How do we meet the aggressive cost targets of a 5 year or less payback for trucks?

Focus on the Key Cost Driving Components
Optimize Silicon of Switching Devices (IGBTs)

Known Wear Out Mechanisms

Less Silicon
Lower Switch Costs
Higher Power Density
Lower Life
Costly cooling system

More Silicon
More Cost
Lower Power Density
Longer Life
Simpler cooling system

TRADE
Anatomy of An IGBT Thermal Cycle

Temperature (Deg C)

- Deceleration
- Sustained power or High Speed
- Hill Climb
- Acceleration
- Idle Shutdown
- Startup Cycle
- Driving Cycles

Lows

Highs

\[ \Delta T_s \text{ are a function of } F(\text{Power}, R_{j,\text{Fluid}}, \text{time}, T_{\text{start}}) \]

\[ \text{Fluid } \Delta T_s \text{ are a function of Cooling Design & Control, } T_{\text{amb}} \]

Outside Ambient

Time (seconds)

Inverter Switch Life is Dependent on Vocation, Duty/Drive Cycle, Driver Habits, Cooling System
Life Prediction Tool Created:

- Transient Thermal Model (Simplified Representation)
  - Foster vs. Cauer Model (simplicity vs physical meaning)

- Real Time Prediction of Junction and Substrate Temperatures Profiles

- Cycle Counting

- Life Damage Predictions

- System Optimization for DT

Goal: Squeeze & Shift

Can Be Adapted for On board Real Time Life Prognostics
Insulated Gate Bipolar Transistor (IGBT) - Opportunities for IGBTs

- Higher Temp Silicon Carbide

- New Packaging
  - Double Sided Cooling
  - New Materials
  - No Wire-bonds

Higher Junction temperatures alone in SiC can reduce overall life

⇒ Need to be able to raise inlet

- Also Need Higher Temperature…
  Film Caps, Circuit Card Components, Current Sensors, Connectors, etc.

Higher Temperature SiC ⇒ Itself is Not the Answer
Circuit Card Cost Opportunities – Lower Costs CCAs

- Limit the number of Circuit Cards
  - Reduces interconnect
  - Increases reliability
  - Less chassis mounting features

- Limit size of circuit cards
  - “Just Enough” Function
  - Combine Control Function (Motor Control and System Control)

- Leverage high volume automotive component cost
  - Automotive components are typically lower temp.

- Combine vibration support with thermal support
  - Analysis tools to predict life of solder joints
  - Low Cycle Fatigue (temperature)
  - High Cycle Fatigue (vibration)
Chassis Cost Opportunities – Lowering Metal Costs

- **Direct water cooled IGBTs simplify Chassis**
  - Low cost castings
  - Less machining

- **Size Matters**
  - Smaller size lowers Material cost ($/lb)
  - Less coring, tooling, handling, finishing, etc

- **Use Common Hardware**
  - Less time on costing machining tools

- **High Voltage/ High Current Connectors**
  - Pluggable connectors simplify chassis but lower reliability.
DC-Link Capacitor & Filter Opportunities

- Laminating bus work is expensive

- Custom caps can be tailored:
  - Less chassis machining
  - Shaped for easier low cost assembly
  - Molding replaces expensive laminating on bus work
High Voltage High Current Connector Considerations

- **Connector Type**
  - Bolted (ring terminal)
  - Pluggable Connector

- **Voltage Isolation**
  - creepage / clearance

- **Current Carrying Capacity**
  - \(~200A – 350\) Arms (Parallel commercial vehicles)
  - \(~700 – 1000\) Arms (Series Transit Vehicles)

- **IP Ratings**
  - IP6K9K & IP67

- **Shield Terminations & Interlocks**
  - Isolated & Low impedance

Low Cost COTS Connectors do not exist for Heavy Duty Vehicle Apps
Need For Common Ratings Definitions

Standard Metrics – The Ratings Game

- **Common Electronics Performance Metrics**
  - Cost ➔ $/kW
  - Power Density ➔ kW/L
  - Specific Power ➔ kW/kg
  - kVA

- **Other Variables**
  - Operating Voltage
  - Efficiency
  - Switching Frequency
  - Control (machine or system control included)
  - Peak Power vs Continuous Power
  - At What Environmental Conditions
    - Ambient
    - Coolant Temperature
  - Design Life/Duty Cycle
Mechanical, thermal and packaging challenges of high voltage, high power electronics for heavy duty propulsion and power management applications.

Summary

- Major differences between **automotive** and **heavy duty** applications have significant cost impacts & drive very distinct design philosophies for power electronics.

- Commonly used Inverter Metrics ($/kW, kW/kg) don’t embody the differences.

- Aggressive cost pressures still exist as **payback** is critical to OEMs and fleet operators.

- **IGBT optimization** is key to managing inverter costs with higher power/torque requirements and more aggressive duty cycles.

- Combining function (**building block approach**) helps reduce costs by lowering part costs, assembly cost, and interconnect costs.
HybriDrive®

Series propulsion system

Parallel propulsion system

Transit Bus

Medium & Heavy Duty

Commercial Trucks

Questions?