# Novel & Ruggedized Power Electronics for Off-Highway Vehicles

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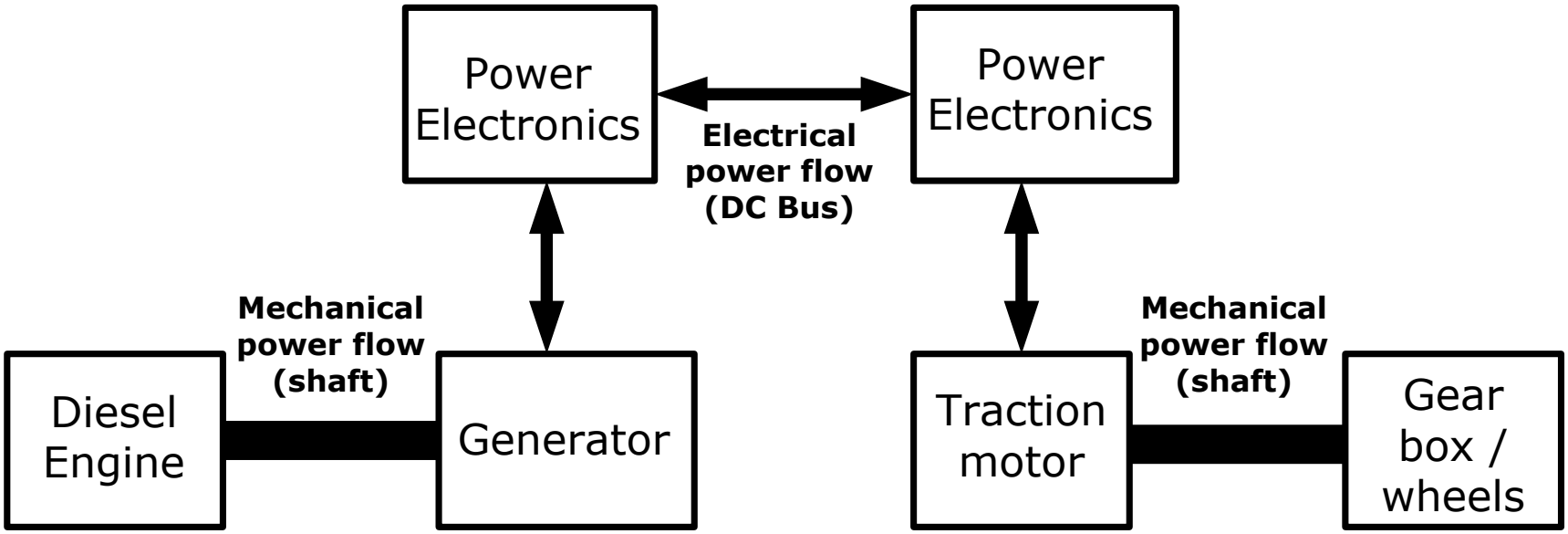
# Outline

- Background/Motivation for power electronics/electric drive use in off-highway vehicles
- Electric drive vehicle system architecture/topology examples
- Performance requirements and attributes of electric drive vehicles and systems
- Example vehicle applications, including benefits over previous vehicle technologies
- Concepts for additional electrification and performance improvement, including Wide Bandgap (WBG) semiconductors
- Conclusions

# Background/Motivation for Electric Drive

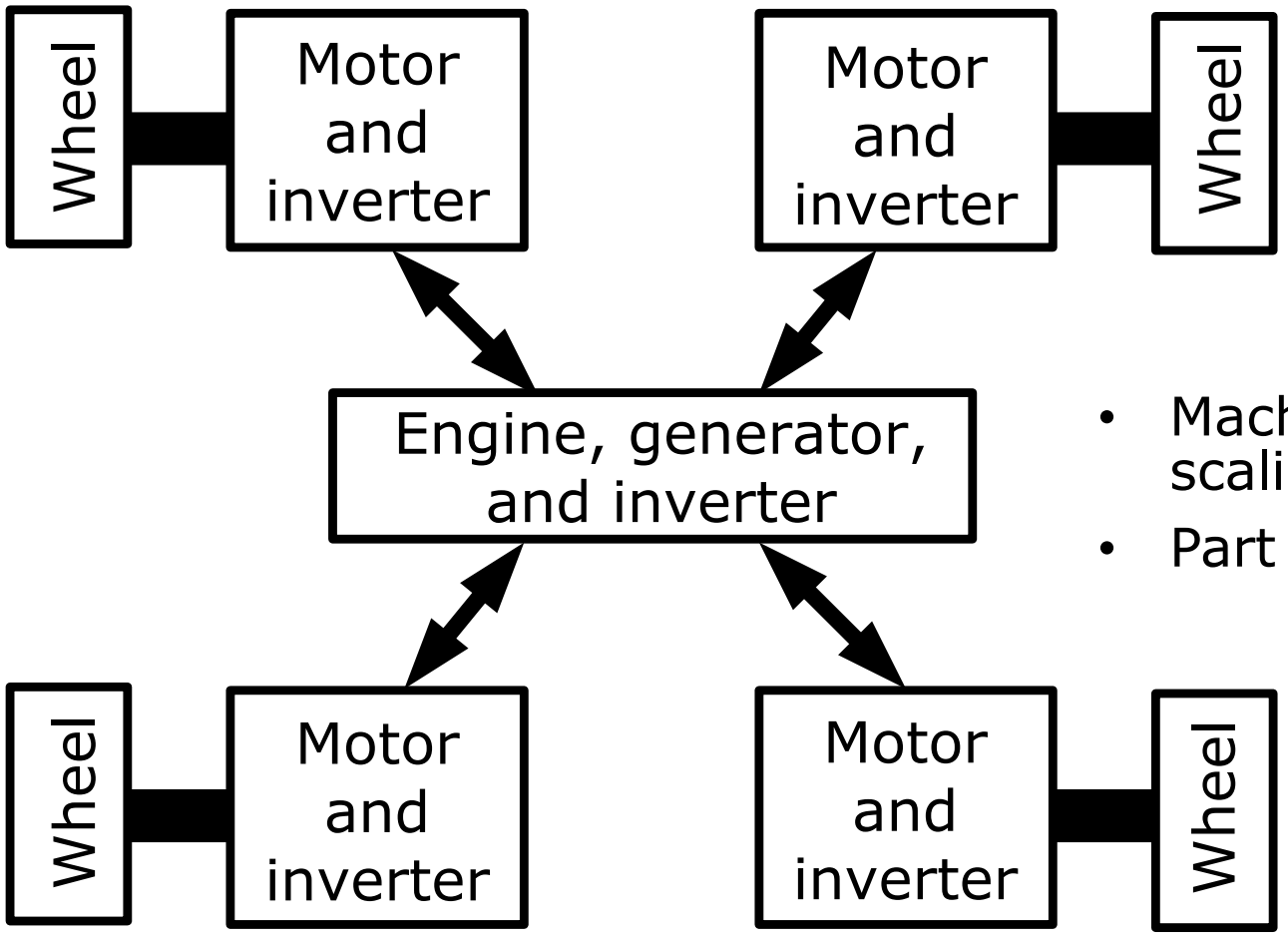
- Electric drives have long been used for the propulsion systems of large vehicles
- High power, high reliability requirements but relatively low volume products
- R & D efforts by automotive industry have resulted in compact machines and drive systems
  - Off-highway vehicles leverage automotive developments
- Challenges of energy costs, emissions restrictions, controllability, increased power and efficiency
- Off-highway equipment applications require a new generation of novel and ruggedized power electronics

# Example Electric Drive System



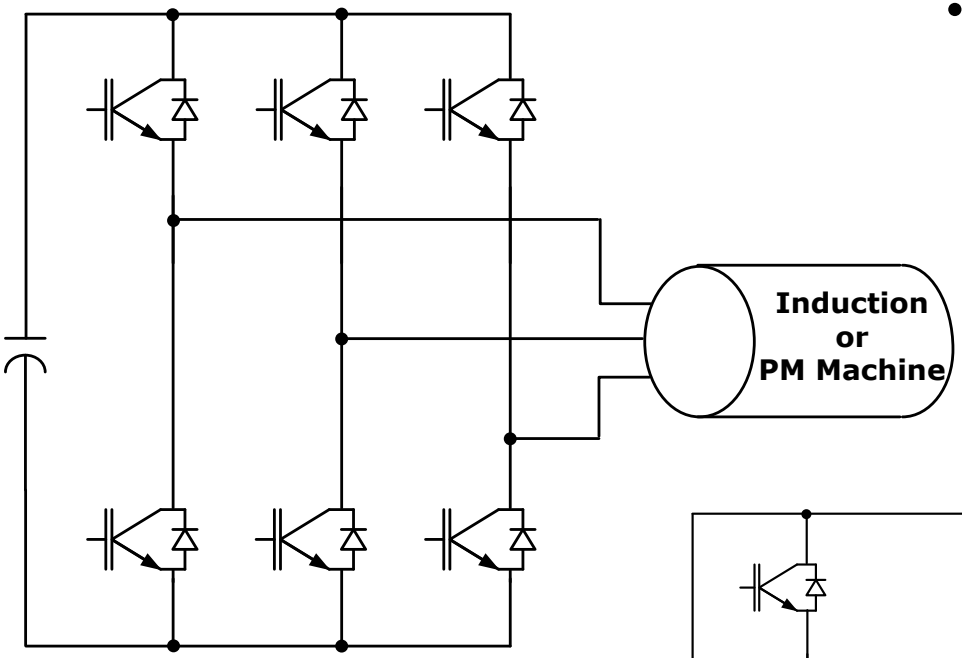

- Internal-combustion engine (typically diesel)
- Generator drive (machine and power converter)
- Traction drive (machine and power converter)
- DC link between power converters
- Gear box / wheels

# Single Generator/Multiple Traction Motor System

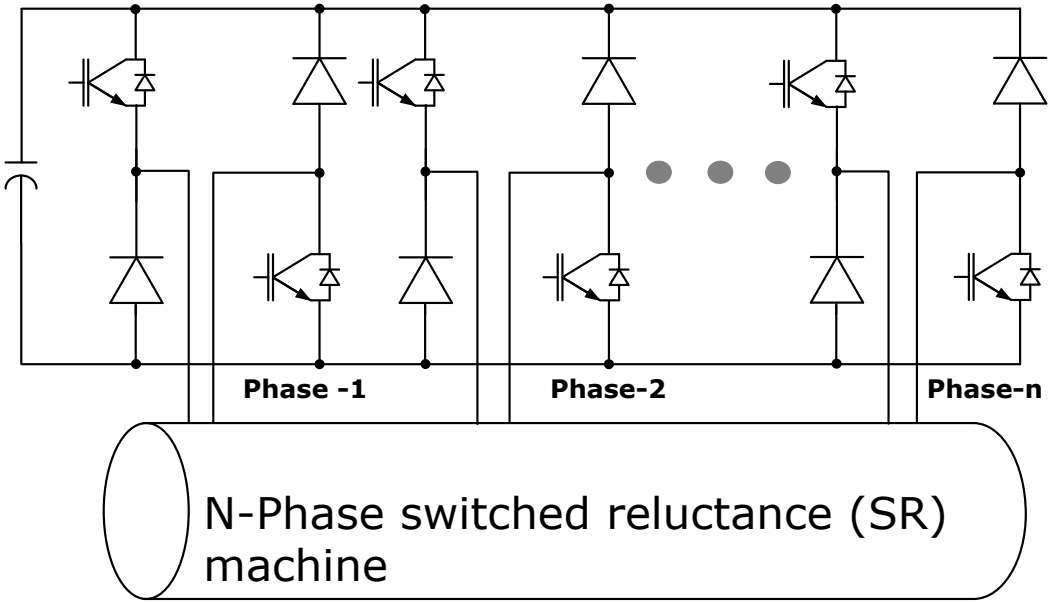



- Machine/inverter scaling
- Part commonality

# Example Electric Drive Converter Topologies




- Different Machine types used based on application requirements:
  - Torque density (vs. power density)
  - Constant Power-Speed Ratio (CPSR)
  - Failure modes



# Attributes and Performance Requirements

- Decreased Fuel Consumption (large vehicles can use $Millions of fuel over their lifetimes)
- Performance, Productivity, and Vehicle Up-time/ Maintenance Enhancements
  - Long vehicle operational life compared to automotive (50k+ hours)
  - Challenge of tighter diesel engine emissions regulations (IT4, FT4)
  - Control system energy flow management with limited energy storage capability (no battery to stabilize DC bus)
    - Rapid energy flow during acceleration, braking, and shifting (DC bus slew rate, if uncontrolled, is tens of kV / second)
  - Less maintenance / longer service intervals
- Torque – Levels, Startup Control, Stall Conditions
  - Very high stall torque and frequent stall events (repeatable torque delivery in both directions upon startup - minimize ripple)
  - Very wide constant power speed ratio (CPSR), ex. 20:1
  - Extra challenges on the control system, position sensors/circuitry, power converter, and machine designs for robust & reliable system

# Attributes and Performance Requirements

- Torque/Power Density – competing with mature & cost effective mechanical, hydraulic, IVT systems
  - Greater energy density needed for power converters and machines
  - Extreme power and thermal cycling of power devices
  - Effective thermal management/advanced cooling systems for both inverters and machines
- Protection, Diagnostics, and Safety
  - Drive system must detect faults, protect itself, & safely shutdown (pinpoint fault codes, prevent cascading failures)
  - Diagnostics methods for numerous voltage levels
  - Operator, bystanders, & service technicians must be protected at all times from high voltage circuitry
  - Possible high voltage safety measures can include:
    - Bonding + reinforced insulation between high and low voltage electronics or the vehicle frame
    - Automatic high voltage discharge/shutdown/interlock systems
    - Warning indicators, product labeling, operator/service personnel training
    - Isolation leakage monitoring system

# Application & Implementation Challenges

- Harsher operating conditions & cycles than industrial or automotive drive systems
- Environmental
  - Operating temperature extremes (-40C to 85C+, -55C storage)
  - High humidity conditions (accelerates wear mechanisms especially when coupled with thermal cycles)
  - Product exposure to chemicals in the field
  - Dusty / dirty / conductive / corrosive environment (operating in coal dust in a mine or salt water atmosphere on a sea coast)
  - High pressure washing/immersion, especially while hot and high voltage electronics are powered
  - Extreme vibration and shock requirements

1200V IGBT-Based Motor Drives

# Application & Implementation Challenges

- High voltage energy storage that is reliable, application-robust, and cost-effective is not yet readily available for these rugged vehicle applications
- Operational
  - Absence of regulated AC mains source on mobile vehicle
  - Power/Thermal cycles due to the continuously cycling nature of the application
  - Foreseeable misuse of vehicles
  - EMC (sensitive electronics in the presence of high E and H fields)
- Safety & Field/Service
  - Safely handling failure modes while limiting vehicle down-time / lost productivity
  - Limp home capability under fault conditions
  - Remote field issues (vehicles often located in extremely remote areas, difficult to access)
  - Ease of maintenance, preferably on-site with no special training

# Example Application – Mining

## Joy Global Loaders

- Models # L-950 to L-2350
- Up to 1,715 kW (2,300 HP) diesel engine, 53 $m^3$ (70 $yd^3$) bucket, and 72,574 kg (160,000 lb.) payload


**Joy Global Super High Lift L2350 – World's Largest Wheel Loader**

**Power Electronics Cabinet**



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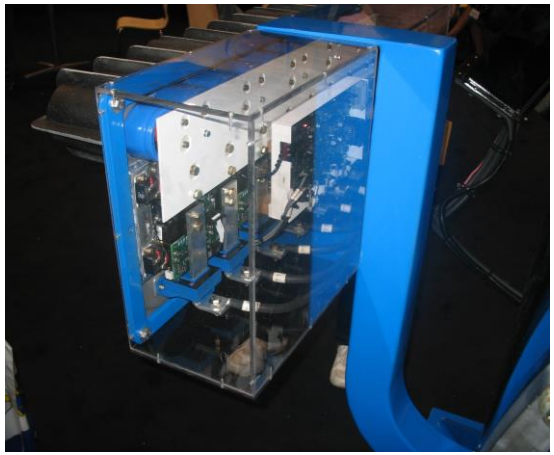
# Example Application – Joy Global

- Independent four wheel traction drive
- Robust, high efficiency SR (switched reluctance) machines
  - Reduced maintenance
  - Enhanced traction control, reduced tire wear
- Enhanced productivity with decreased fuel consumption (up to 45%)
  - Energy recovery in electric braking
  - Faster hydraulic and work cycle times
- Less fluids required (less maintenance, cost)
- Scalable power electronics system across loader line (same converter used everywhere, >8:1 power range)

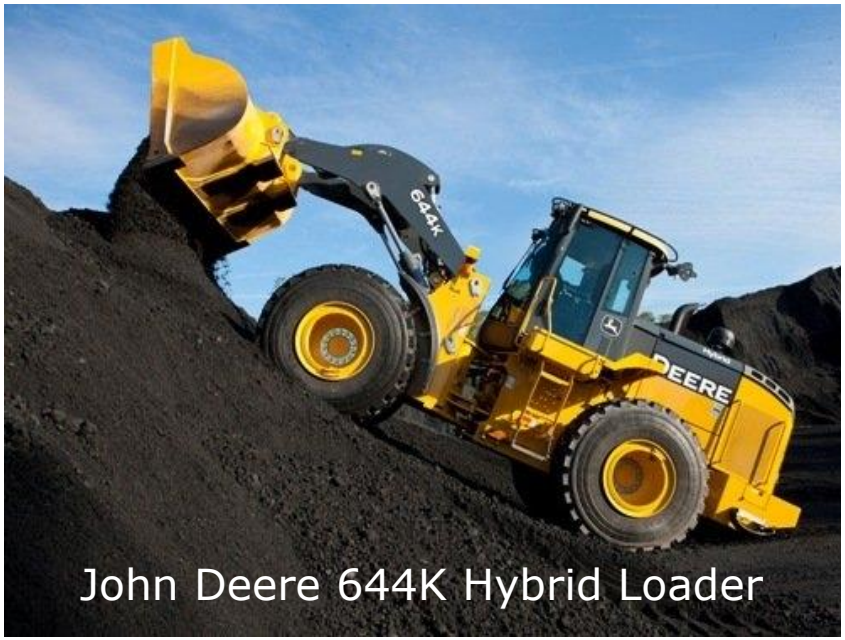

Fuel Savings



Power Electronics

# Example Application – Construction

**John Deere 644K Hybrid Loader**



John Deere 644K Hybrid Loader

- World's 1st E-drive Construction Production Wheel Loader
- Hybrid version uses 6.8L vs. 9.0L engine
- Productivity/Uptime/ Operating costs
  - Estimated 25%+ fuel savings
  - Easier to use/lower operator skill level/less fatigue
  - Higher performance/more productive
  - Allows use of engine's max efficiency operating point
- -3dBa sound reduction (plus even more perceived)

# Example Application – Turf

## John Deere Golf Course Mowers

- Electric cutting reels
- Consistent reel speed, optimal cut in all conditions
- Improved turf appearance and even playing
- Allows lower engine speed
- Quieter operation
- Reduction of potential hydraulic leak points
- Easier maintenance
- Fuel savings

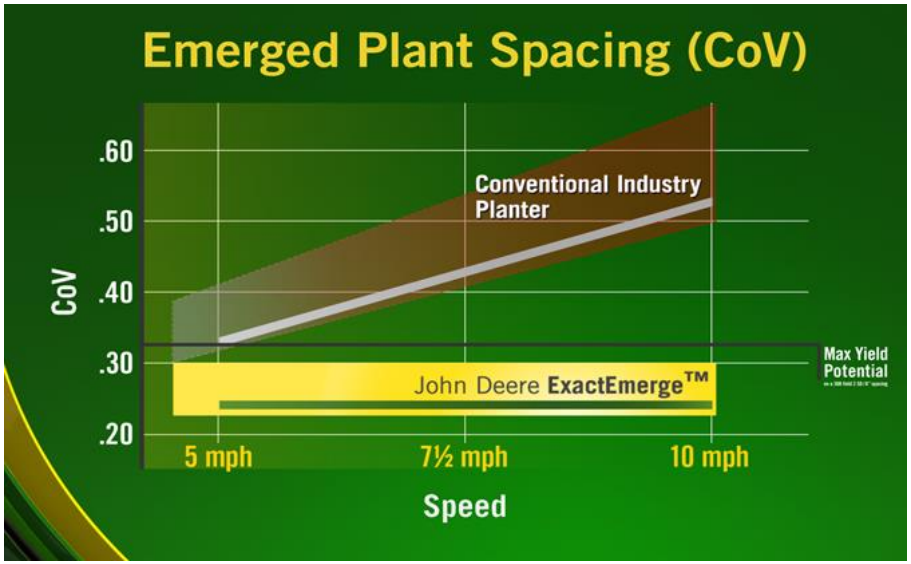
E-Cut™ 2500E Greens Mower

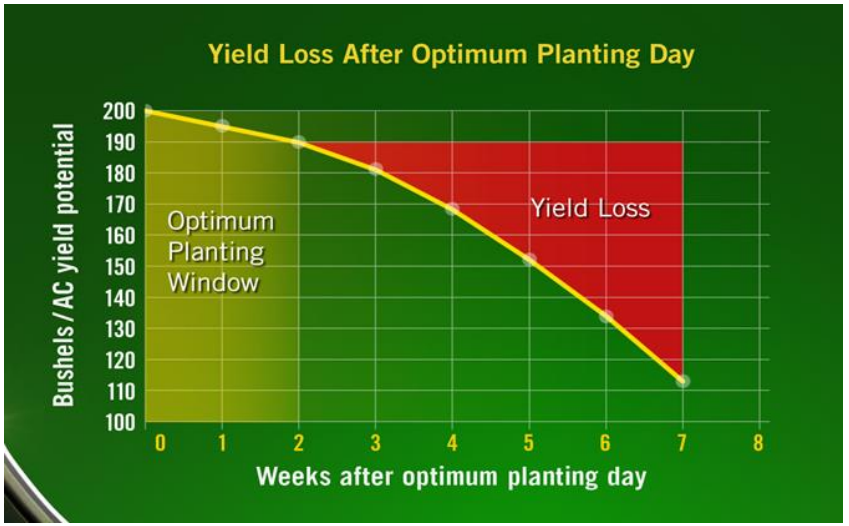
E-Cut™ 8500 Fairway Mower

# Example Application – Seeding

## John Deere ExactEmerge™ Planting System

# Customer Value From Electric Drive Planting



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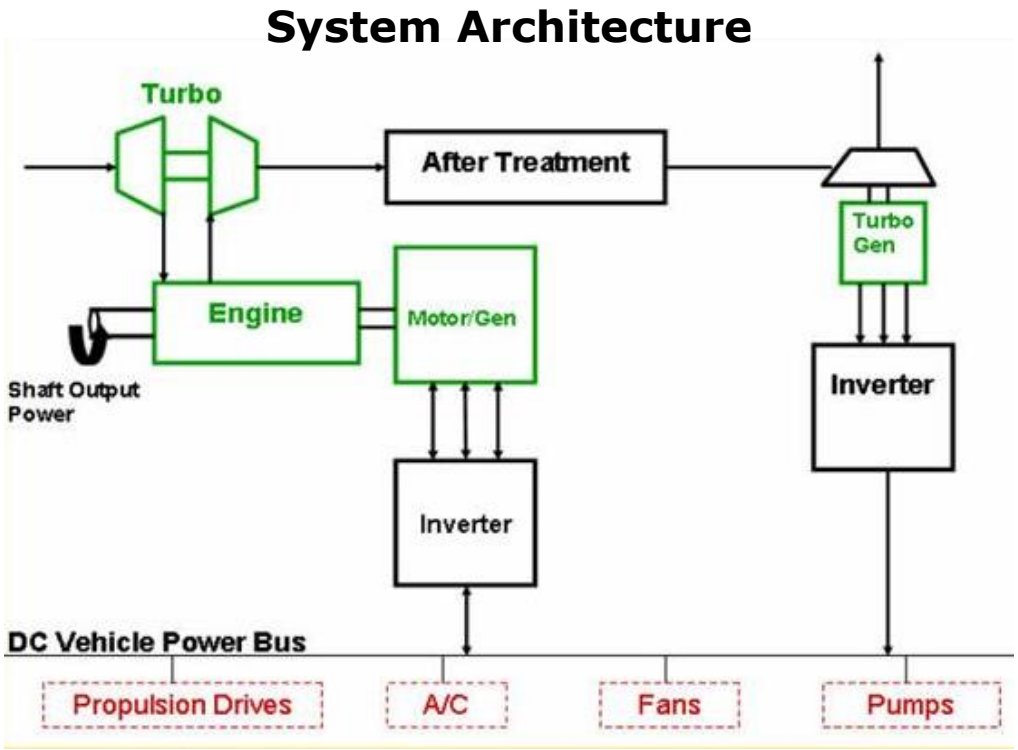
# Electrification Expansion Opportunities

- Leveraging/increasing value of electric drive system
- Energy storage systems for increased energy recovery, performance boost, or engine off operation
  - Electrical (battery, ultracap)
  - Mechanical/Inertial (flywheel)
  - Pressure (hydraulic oil, compressed air)
- Alternator and/or starter replacement
  - Isolated DC/DC converter technologies
- Export power
- Electrify auxiliaries
  - Variable speed as needed

# Electric Turbo Compounding

- Recover additional energy from engine exhaust
- Add-on feature once vehicle is electrified
- Efficiency boost
- Controlled power flow/ back pressure using inverter
  - Max efficiency at all loads and speeds
- Power available for flexible use (electrical or mechanical loads in hybrid system)



# Wide Bandgap (WBG) Semiconductors vs. Silicon

- Higher operating voltage
- Faster switching
- Higher temperature operation
- Increased thermal conductivity
- Easier integration of electrical energy storage (DC/DC converters)
- Improved motor control, reduced current ripple/THD
- Higher power density and efficiency systems
  - Reduced size, weight, fuel consumption
- Open Issues - Cost, robustness, short circuit ratings, high temp interconnect/packaging, insulation systems impact, long-term field reliability?

# Conclusions

- Energy costs, engine emissions restrictions create need for more efficient vehicles while meeting/exceeding performance, productivity, and cost metrics
  - Electric drives are an enabling technology
- Demand for robust, high performance electric drive systems to replace existing mechanical systems
- Unique application and implementation challenges
- Significant performance improvements demonstrated
- Improved energy recovery technologies, expansion applications, & WBG can optimize electric drive system value
- Leverage automotive efforts
- Future work needed in electric drives
  - Reliability, product packaging, thermal management, cost competiveness

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