Electric Drives for Battery Electric Vehicles

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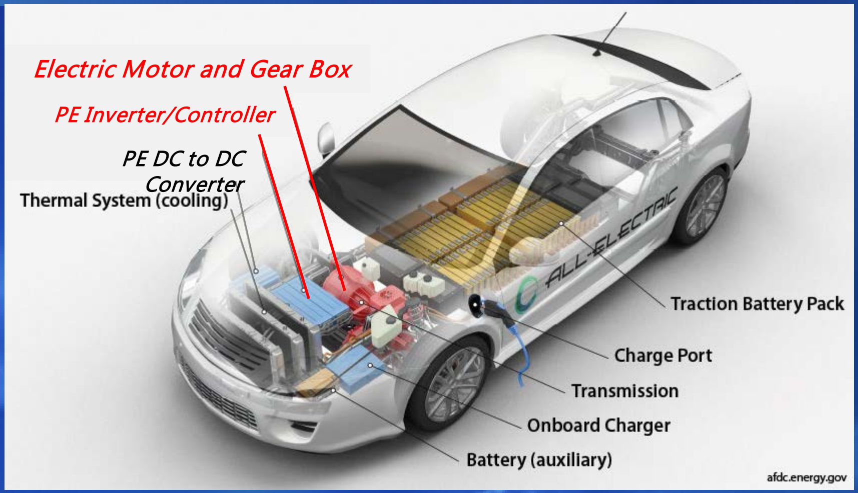
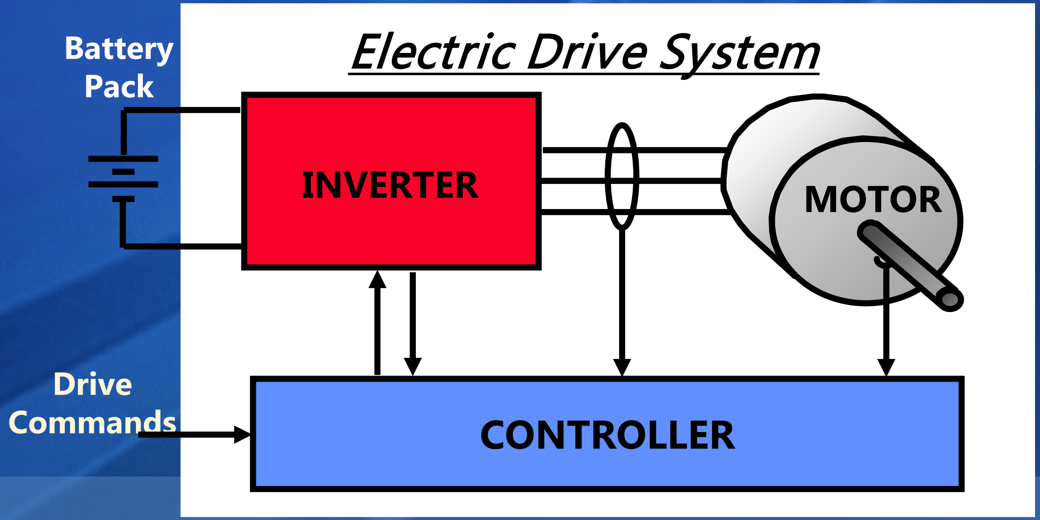
Overview

- Fundamental Definitions
- Reasons for Industry Conversion on One Electric Drive Type, Based on PMSM
- Current State-of-the-Art
- Potential Advances in Electric Drive Technologies

BEV Electric Drive System

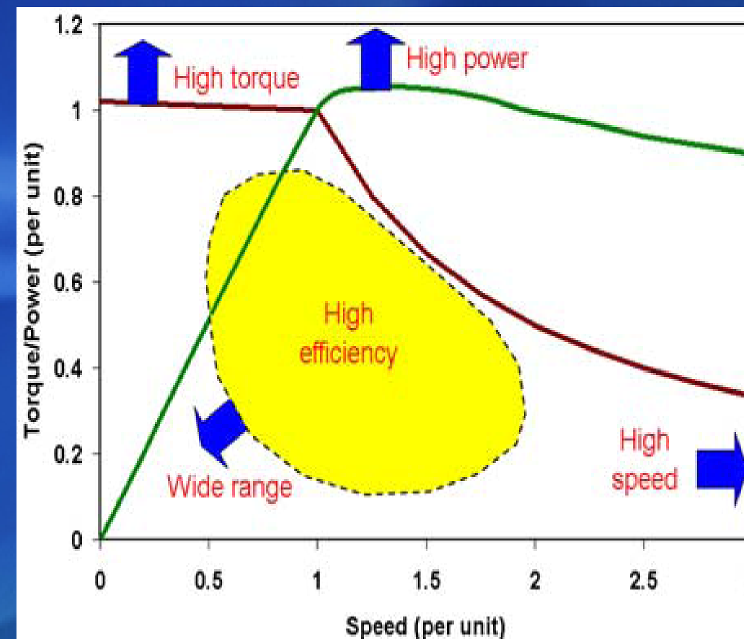
- *Electric Motor*
  - *Converts electric energy to mechanical energy*
- *Gearbox*
  - *Converts motor speed to wheel speed*
- *Power Electronics*
  - *Inverter: converts DC to AC*
- *Controller*
  - *Provides electronic signals to achieve desired drive output*
- *Sensors*
  - *Current and rotor position*



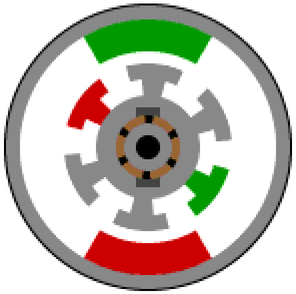


Requirement for Propulsion Drives

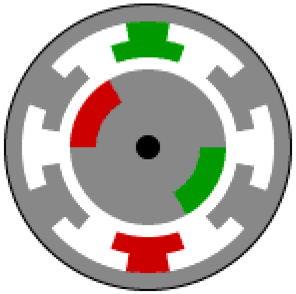
- *High torque density and power density*
- *High torque* **for starting, at low speeds and hill climbing, and** *high power* **for high-speed cruising**
- **Wide speed range, with a constant power operating range of 3–4 times the base speed**
- *High efficiency* **over wide speed and torque ranges, including low torque operation**
- **Intermittent overload capability, typically twice the rated torque for short durations**
- **High** *reliability and robustness* **appropriate to the vehicle environment**
- **Acceptable** *cost*
- **Low acoustic noise and low torque**



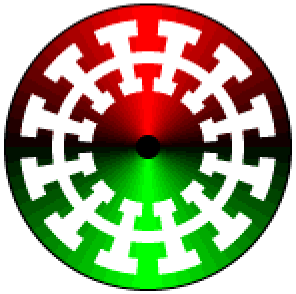
Different Types of Motors



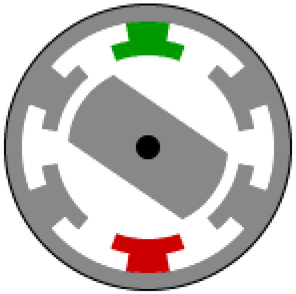
DC Motor



PM Synchronous Motor



Induction Motor



Switched Reluctance Motor

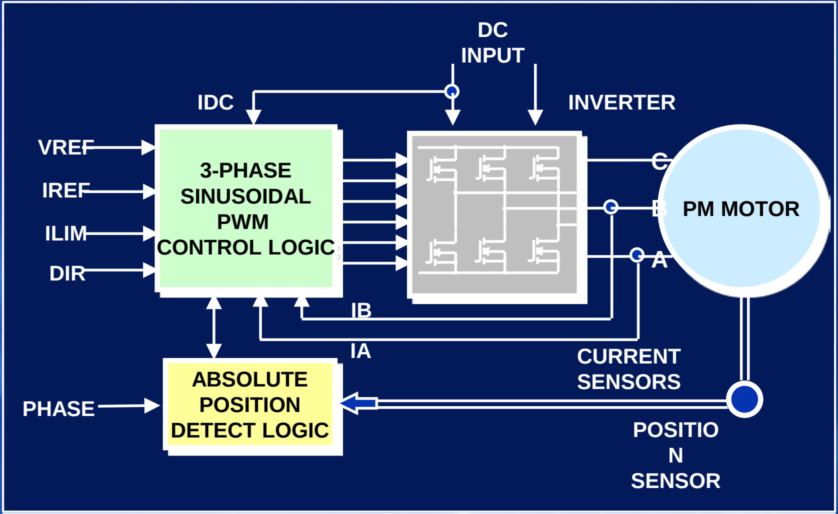
- *Stationary magnetic field*
- *Mechanical Commutation, using brushes*
- *Requires power switches for control*

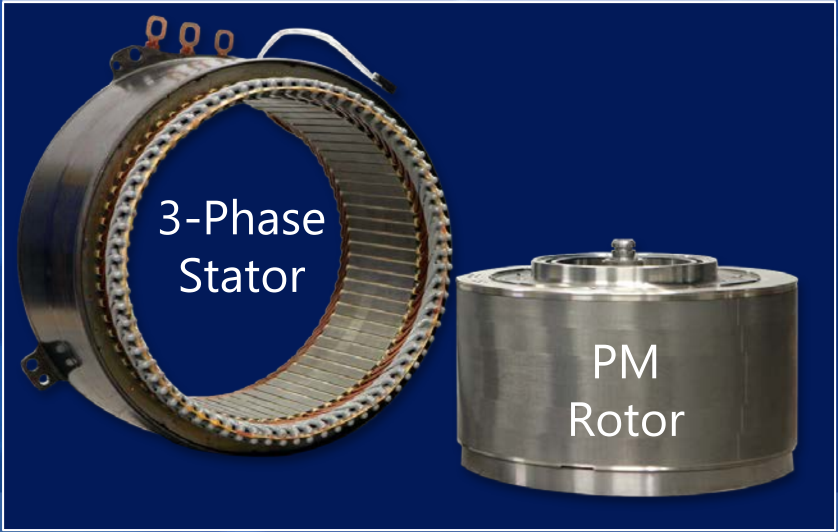
- *Rotating magnetic field*
- *Brushless*
- *Commutation is done using electronic power switches*

OEMs Drive of Choice

Permanent Magnet Synchronous Motor Drive (PMSM)

- Brushless
- PM rotor
  - High energy NeFeB
- Single-Stage Gearbox
- 3-phase stator windings
- 3-phase inverter
  - Sinusoidal control



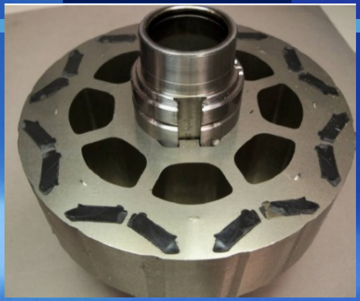


Why Brushless ?

Attributes	Brushed	Brushless
Commutatation	Mechanical	Electronic
Maintenance	-	+
Consistency over Life	-	+
Torque Density	-	+
Efficiency	-	+
Speed Range	-	+
Torque Ripple	+	-
Inertia	-	+
Thermal	-	+
Mechanical Noise	-	+
EMI	-	+
Cost	+	-

Why PM Motor ?

PM Rotor



- Many different PM rotor configurations
- Highest performance and cost
- Field excitation produced by magnets

IM Rotor

- Al bar windings shorted at ends by Al rings (die cast)
- Low cost, industry workhorse
- Higher efficiency at high speed

SRM

- Simple, rugged rotor structure
- Rotor losses at high speed due to flux pulsations
- Large radial forces result in acoustic noise
- Non-sinusoidal excitation
- More complicated, higher VA rated inverter

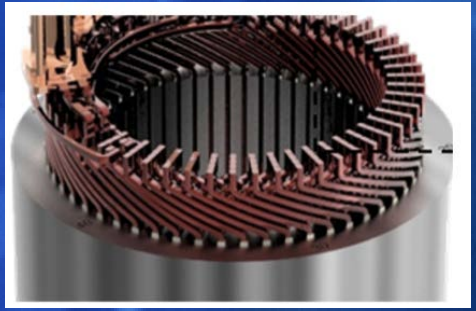
Metric / Machine	Cost	Reliability	Torque Density	Efficiency	Acoustic Noise	Controller Cost	Sensor Cost	Packaging Flexibility
Induction	3	3	2, 3 for Al, Cu	2, 3 for Al, Cu	4	3	3	2
Permanent Magnet	0	3	4	4	3	4	1 Due to Fld Wkg, # poles	4
Switched Reluctance	4	4	3	2	0	1	2	2

Scale: 0 – worst, 1 – below average, 2 – average, 3 – above average, 4 – best

Motors – Current State-of-the-Art

- *Industry converged on using IPSM with RE magnets as the drive motor for BEVs due to its superior efficiency, torque, and power density, despite its cost disadvantage compared to IM.*
  - IM is used on second axle in a two-motor system to improve 0-60 mph performance and enhance high speed efficiency (Tesla, GM).
- *Use of special material, design and manufacturing techniques to maximize efficiency, reduce cost:*
  - Magnets with low Dy content
  - Magnets housed in deep rotor slots, protection and robustness
  - Thin, low loss, electrical steel laminations, with high flux carrying capabilities
  - Flat wire, for higher slot fill, higher torque density
  - Hairpin winding, minimize winding overhang, its loss and motor size
- *Industry converged on single-stage gearbox with a gear ratio of 7:1 - 10:1*

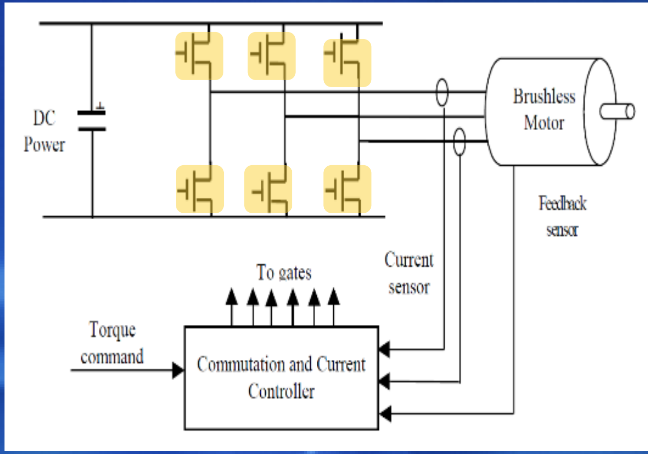
Traditional stranded windi

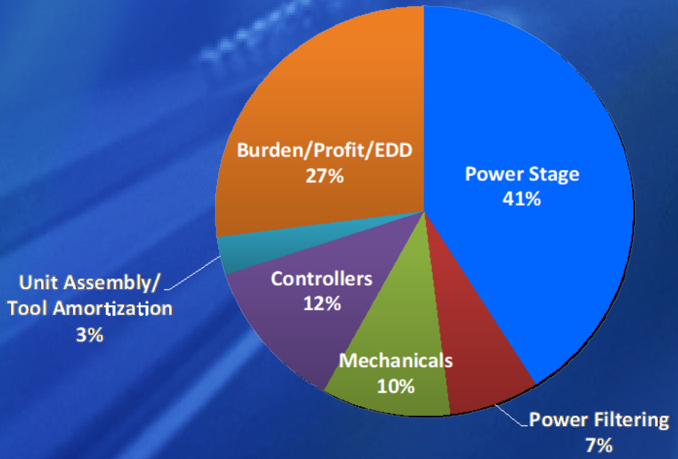

*Hairpin winding**

** SOURCE: Villani (2018)*

PE – Current State-of-the-Art

- *The power switching devices and associated thermal system, interconnections, etc. dominate inverter size and cost*
  - Most OEMs’ use silicon-based IGBTs power-switching devices in their power electronic circuitry
  - Lower loss devices allow reduced cost thermal systems and smaller size
- *Major improvements were introduced through:*
  - Design optimization of the IGBTs for minimum loss
  - System integration to improve efficiency and power-density while maintaining a capability for scalability
  - High performance control (Dead Beat Direct Torque Control, DB-DTC, with loss observer, reduces drive loss and enhances drive efficiency.
  - Acoustic and EM noise reduction
  - Improved reliability (Fault Tolerance, Diagnostics & Prognostics)
- *Wide Band Gap (WBG) Semiconductors offer significant size and efficiency advantages, but are still in limited use in automotive (SiC at TESLA).*





Inverter Cost

Motors - Potential Advancements

- *Motor Mass and Cost*
  - *Increase Motor Speed*
    - Doubling the motor speed for the same output power would result in a motor with half the active length, weight, and active material cost, while the gear weight and cost and noise would increase. An optimum gear ratio should be sought
  - *Use less RE magnet material*
    - *Use the more abundant Cerium (Ce) instead of Dysprosium (Dy) and maintain performance*
    - *Lower temperature grade RE PM (less Dy),* Improved cooling and control (hotspot observer)
      - ✓ Lower losses (loss minimization DB-DTC control)
    - *Higher speed (reduced torque for given power)*
      - ✓ Lower magnet mass
    - *Thinner magnets (hotspot observer + demag control)*

<u>*Motor Design Equation*</u>

- *Motor Power P = Motor Torque T * Motor Speed n*
- *Motor Torque* $T = \pi/4 * D_a^2 * L_a * B_m * A_m$

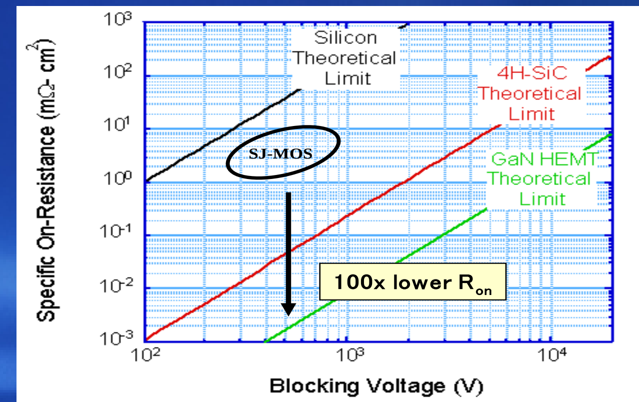
Where,

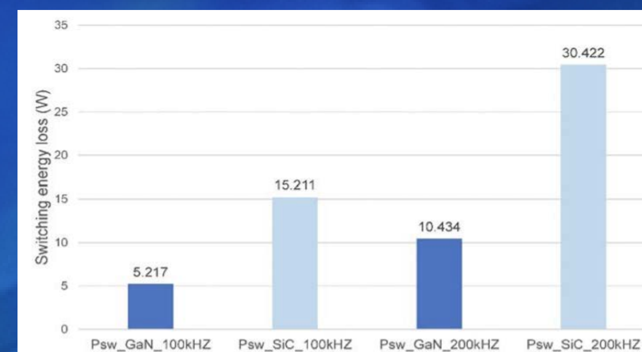
D_a	Diameter at air gap
L_a	Active motor length
B_m	maximum air gap flux density
A_m	Maximum stator current sheet

- *So, for the same power the motor active length is inversely proportional to motor speed maintaining other parameters constants*

PE - Potential Advancements

- *PE Cost and Efficiency*
  - *Wide band gap (WBG) devices (SiC and GaN) receive significant attention by most OEMs:*
    - Offer significant performance advantages over Silicon based IGBT devices, due to their lower on-resistance, and their ability to operate at higher Voltages and temperatures
    - WBG devices show great potential to dramatically improve inverter size, efficiency, and cost
    - SiC is further developed, but GaN (on Si) has the potential of being lower cost
  - ***Commercially available WBG devices do not meet automotive performance and cost requirements***
  - *Fast switching WBG Semiconductors offer even higher efficiencies. They allow reduced cost thermal systems and smaller sizes*





- *100x lower loss → Higher efficiency →*
- *Higher switching frequency*
  Lower switching → → loss & inverter cost
- *Higher operating temperature Lower cooling cost*
- *GaN-on-Si substrate Low-cost volume manufacturing*

Estimated impact of Advanced Technologies

Motors

- *Use of the new Cerium magnets and Increasing gear ratio to 14:1 for a mid-size vehicle (Tesla Model 3 rear), is estimated to achieve a weight and cost reduction of approximately 5 and 16 %, respectively.*
  - *Assumptions:*
    - ***New Cerium-based magnet material would reduce magnet cost by 30 percent from current prices.***
    - ***New gearing with a higher gear ratio of 14:1 instead of the 9:1 assumed in current systems.***

Power Electronics

- *WBG devices are likely to dominate with GaN on Si being most cost effective (if device architectures could lead to usable performance).*
- *There is a potential for inverter efficiency increase to 99% (from 96%), while reducing the size and weight of the cooling system components by ca. 75%. This efficiency gain translates to adding roughly 9-10 miles to a vehicle with a 300 mile range.*
  - *Assumptions:*
    - Baseline for the estimates is today's Tesla Model-3 inverter, using SiC devices and a high degree of integration.
    - Cost of GaN power switching devices is 25% lower than today's SiC; this decrease in cost includes the effects of resolving manufacturing issues and increasing production volume
    - The reduced conduction and switching loss (at high switching frequency) will lead to reducing cooling needs by 75%
    - Switching at higher frequency (100 kilohertz) will result in reduced filtering components size, weight and cost by 75%
    - Natural electronics cost reduction trajectory leads to 25% controller cost reduction
    - Inverter cost includes power stage, cooling and mechanical assembly, filtering, and electronic controller only. It does not include power distribution, DC/DC converter, or charging electronics.

Summary:
Motors & Power Electronics

Motor Technology

- IPSM motors with lower cost RE magnets will continue to dominate due to their superior efficiency. IM is best for second axle.
- Using Ce-based RE magnets instead of Dy-based and Increasing gear ratio to 14:1 could lead to significant weight and cost reductions.

Power Electronic Technology

- WBG power switching devices are likely to dominate due to efficiency gains and reduced cooling system size and weight.
- GaN-on-Si could become most cost effective. Switching GaN devices at higher frequencies could further improve power density and efficiency

Thank You

Examples: Propulsion Motor Performance Status

TABLE 5.1 Propulsion Motor Performance Status Summary – Motor Only

Application	Power (kW)	Gear Ratio	Motor Only Weight[a] (kg)	Power Density[a] (kW/kg)	Max Motor Torque (Nm)	Torque Density[a] (Nm/kg)	Motor Only Cost[a] ($)	Specific Cost[a] ($/kW)
GM Bolt	150	7.05	43	3.5	360	8.4	714	4.8
Tesla Model 3 Rear	188	9.03	45	4.2	380	8.4	750	4.0
BMW i3	125	9.7	31	4.0	250	8.1	496	4.0

[a] Estimated.

SOURCE: Committee generated data, partially based on motor weight and cost data presented by Munro to the committee on September 24, 2019.

TABLE 5.2 Propulsion Motor Performance Status Summary – Motor with Gearbox

Application	Power (kW)	Gear Ratio	Motor + Gear Weight[a] (kg)	Power Density[a] (kW/kg)	Max Motor Torque (Nm)	Output Torque Density[a] (Nm/kg)	Motor + Gear Cost[a] ($)	Specific Cost[a] ($/kW)
GM Bolt	150	7.05	59	2.5	360	43.0	895	6.0
Tesla Model 3 Rear	188	9.03	71	2.6	380	48.3	1044	5.6
BMW i3	125	9.7	49	2.5	250	49.5	703	5.6

[a] Estimated.

SOURCE: Committee generated data, partially based on motor weight and cost data presented by Munro to the committee on September 24, 2019.

Estimated Potential Impact of Possible Motor Technology Advancements

TABLE 5.3 Potential Impact of Future Motor Technologies on Various Vehicle Classes

BEV 300 Motor Technologies	Vehicle Class (Power, Torque)	Technology Cost by Class	Motor Total Weight, Cycle Efficiency
• Cerium magnets	Small (110 kW, 142 Nm)	\$ 531	43 kg, 90.5%
• Higher gear ratio (14:1)	Medium (180 kW, 233 Nm)	\$ 868	67 kg, 91%
	Crossover (150 kW, 194 Nm)	\$ 724	57 kg, 90.7%
	SUV (220 kW, 285 Nm)	\$ 1061	81 kg, 91.2%
	Truck (250 kW, 324 Nm)	\$ 1206	92 kg, 91.5%

- *For mid-size vehicle (Tesla Model 3 rear), there is a potential for weight and cost reduction of approximately 5 and 16 percent, respectively*
- *Assumptions:*
  - *New Cerium-based magnet material would reduce magnet cost by 30 percent from current prices.*
  - *New gearing with a higher gear ratio of 14:1 instead of the 9:1 assumed in current systems.*

Examples: Inverter Performance Status

TABLE 5.4 Power Density and Cost of Current Inverter Topologies

Application	Power(kW)	Inverter Weight[a] (kg)	Power Density[a] (kW/kg)	Inverter Cost[a] ($)	Specific Cost[a] ($/kW)
17 GM Bolt	150	10	15.0	700	4.7
Tesla Model 3	188	5.5	34.1	800	3.5
BMW i3	125	19.0	6.6	1100	8.8

[a] Estimated.

SOURCE: Committee generated data, partially based on motor weight and cost data presented to the committee on September 24, 2019.

- ***Not meant for side-side comparison:***
  - *Each adopts a different integration strategy*
  - *They adopt different switching technologies: GM-Bolt and BMW-i3 use IGBTs, while Tesla-Model 3 uses SiC switches*
  - *Increasing gear ratio to 14:1 could lead to significant cost reductions.*

Estimated Potential Impact of Possible Inverter Technology Advancements

TABLE 5.5 Potential Impact of Future Inverter Technologies on Various Vehicle Classes

BEV 300 Inverter Technologies	Vehicle Class (Power)	Technology Cost by Class	Inverter Weight, Efficiency
• GaN-based power switching devices	Small (110 kW)	\$ 334	2.3 kg, 98.5%
	Medium (180 kW)	\$ 471	3.8 kg, 99%
• High frequency switching (100 kHz)	Crossover (150 kW)	\$ 412	3.2 kg, 98%
	SUV (220 kW)	\$ 550	4.7 kg, 99%
	Truck (250 kW)	\$ 609	5.3 kg, 99%

- *There is a potential for inverter efficiency increase to 99 percent (from 96 percent), while reducing the size and weight of the cooling system components by ca. 75 percent. This efficiency gain translates to adding roughly 9-10 miles to a vehicle with a 300 mile range.*
- *Assumptions:*
  - *Baseline for the estimates is today's Tesla Model-3 inverter, using SiC devices and a high degree of integration.*
  - *Cost of GaN power switching devices is 25% lower than today's SiC; this decrease in cost includes the effects of resolving manufacturing issues and increasing production volume*
  - *The reduced conduction and switching loss (at high switching frequency) will lead to reducing cooling needs by 75 %*
  - *Switching at higher frequency (100 kilohertz) will result in reduced filtering components size, weight and cost by 75 %*
  - *Natural electronics cost reduction trajectory leads to 25 % controller cost reduction*
  - *Inverter cost includes power stage, cooling and mechanical assembly, filtering, and electronic controller only. It does not include power distribution, DC/DC converter, or charging electronics.*

Factors Influencing Drive System Cost

Factor	Impact
Drive Efficiency	• Less battery kWhr, reduced cooling system costs,… • Lower system cost
Motor Speed	• Higher speed lowers motor volume, mass and cost
High Frequency & Temperature Electronics	• Lower volume, mass and cost due smaller magnetic components, capacitors • Lower cooling costs
High Performance Control	• Loss minimization (Dead Beat Direct Torque Control (DB-DTC) with loss observer) • Sensor reduction/elimination (observers) • Acoustic and EM noise reduction • Improved reliability (Fault T, D&P)
System Integration	• Shared housing, cooling, AC cable elimination, lower cost • Reduced acoustic and EM noise • Higher efficiency (no cable losses)