Electric and Hybrid Vehicles: Current trends and future strategies

Kaushik Rajashekara

Outline

• Brief History of Electric Vehicles
• Electric vehicles
• Hybrid Vehicles
• Electric Vehicle Charging
• Challenges
• Next Steps
History of Electric Vehicles

**EV History**

- 1834 - Non-rechargeable battery powered electric car - invented by Thomas Davenport
- 1851 - Non-rechargeable 19-mi/h electric car.
- 1859 - Development of lead acid storage battery.
- 1874 - Battery powered carriage.
- Early 1870's - Electricity produced by dynamo-generators.
- 1881 First electric vehicle (Gustave Trouve), Int’l Exhibit of Electricity, Paris, FR.
- 1890's : EV’s outsold gas cars 10 to 1, Oldsmobile and Studebaker started as EV companies
- 1900 - 4,200 automobiles sold:
  - 40% steam-powered
  - 38% electric powered
  - 22% gasoline powered
- 1920’s - EVs disappear and ICEVs become predominant.
Early Electric Vehicles

Disappearance and Resurgence of EVs

- **Factors that Led to the Disappearance of EV**
  - Invention of starter motor in 1911 made gas vehicles easier to start.
  - Improvements in mass production of Ford model T (gas-powered car) vehicles which sold for $260 in 1925 compared to $850 in 1909. EVs were more expensive.
  - Rural areas had very limited access to electricity to charge batteries, whereas, gasoline could be sold in those areas.

- **Resurgence of EVs in 1960’s**
  - Resurgence of EV research and development in 1960’s due to increased awareness of air quality.
  - Congress introduces bills recommending the use of EVs as a means of reducing air pollution
US Transportation sector accounted for:
- About 1/3rd of total energy use and greenhouse gas emissions
- More than 70% of petroleum consumption
- In 2018, greenhouse gas emissions from transportation accounted for about 28% percent of total U.S. greenhouse gas emissions, making it the largest contributor of U.S. greenhouse gas emissions.
- In terms of the overall trend, from 1990 to 2018, total transportation emissions have increased because the number of vehicle miles traveled increased by 46% percent from 1990 to 2018.

Total 2019 CO2 emissions: 34GT (Global)
- USA: 4.9GT; China: 9.8GT; India: 2.5GT

https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
GM Impact 1990/EV1

- The Impact prototype was powered by two induction motors, one driving each front wheel. The battery pack consists of 32 compact 10-volt Delco Remy lead-acid batteries, connected in series. The inverter for converting the battery voltage to ac has 288 MOSFETs, each leg consisting of 24 parallel connected devices, switching at about 20 KHz. The slip frequency of the AC current was varied to maintain the highest possible efficiency throughout the RPM range. Each motor's output is transmitted to the tires via a 10.5:1 planetary gear unit.

  - Motor Type: Three phase induction motor
  - Max. motor output: 57 bhp @ 0 to 6600 rpm (per motor)
  - Motor speed at 60 mph: 9500 rpm
  - Top speed: 100 mph (rev. limited to 75 mph)
  - Torque: 47 lb-ft @ 0 to 6600 rpm (per motor)
  - Inverter type: Dual MOSFET inverter
  - Frequency range: 0-500 Hz
  - Battery type: Lead acid, 32, ten volt batteries in series.
  - Capacity: 42.5 amp. hour, 13.6 KWh
  - Battery weight: 395 Kg
  - Battery charger: Integral with dual inverter package
  - Recharge Time: 2 hrs (80%)
  - Range: 120 miles @ 55 mph
  - Acceleration(0 to 60 mph): 8 seconds
  - Vehicle weight: 1000 Kg

- GM’s Impact was the first production intent EV announced by a major car manufacturer. Impact technology led to the production of EV1 electric vehicles.
GM EV1 1996-1999

- Top Speed – 125 mph
- 2 Speed Transmission
- Range – 220 miles
- Full charge in 3.5 hrs (with 70 amp home charging station)
- Shaft Drive
- Weight – 2690 lbs
- 6,831 Lithium Ion batteries (laptop)
- Each cell is independent
- 100,000 mile life expectancy
- 3-phase, 4-pole electric induction motor, 215 kW
- Propels car 0 – 60 mph in under 4 seconds
- 85% – 95% efficient

Tesla Roadster - 2008

- Top Speed – 125 mph
- 2 Speed Transmission
- Range – 220 miles
- Full charge in 3.5 hrs (with 70 amp home charging station)
- Shaft Drive
- Weight – 2690 lbs
- 6,831 Lithium Ion batteries (laptop)
- Each cell is independent
- 100,000 mile life expectancy
- 3-phase, 4-pole electric induction motor, 215 kW
- Propels car 0 – 60 mph in under 4 seconds
- 85% – 95% efficient

Discontinued
**Tesla Model S - 2012**

**Powertrain:**
Model S is a rear wheel drive electric vehicle. The liquid-cooled powertrain includes the battery, motor, drive inverter, and gear box. Microprocessor controlled, 60 kWh lithium-ion battery (230 miles range, it is 300 miles with 85 kWh), Three phase four pole induction motor with copper rotor (310 kW, 600 N·m), Inverter with variable frequency drive and regenerative braking system, and Single speed fixed gear with 9.73:1 reduction ratio.

**Charging:**
- 10 kW capable on-board charger with the following input compatibility: 85-265 V, 45-65 Hz, 1-40 A (Optional 20 kW capable Twin Chargers increase input compatibility to 80 A)
- Peak charger efficiency of 92%
- 10 kW capable Universal Mobile Connector with 110 V, 240 V, and J1772 adapters

**Electric Vehicles (EV)**

- **Nissan Leaf**
- **Tesla Model S**
- **KIA Soul**
- **BMW i3**
- **Mahindra E20 Plus**
- **Ford Focus**
- **Chevrolet Volt**
- **Mitsubishi i-MIEV**
- **BYD e6**
### 2017 Nissan Leaf

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horsepower</td>
<td>107 HP</td>
</tr>
<tr>
<td>MPGe(City/Highway)</td>
<td>120/101</td>
</tr>
<tr>
<td>Torque</td>
<td>187 lb-ft</td>
</tr>
<tr>
<td>Range</td>
<td>107 miles</td>
</tr>
<tr>
<td>Battery Type</td>
<td>Li ion</td>
</tr>
<tr>
<td>Battery Energy</td>
<td>30 kWh</td>
</tr>
<tr>
<td>Battery charger</td>
<td>6.6 kW</td>
</tr>
<tr>
<td>Charging time</td>
<td>6 hours</td>
</tr>
</tbody>
</table>

*Battery Housing*

---

### Hybrid Vehicles
Electric and Hybrid Vehicle Configurations

- **Pure Electric**
- **Series Hybrid**
- **Parallel Hybrid**

**EV, HEV, and PHEV**

- **Hybrid EV (HEV)**
- **Plug-In Hybrid EV (PHEV)**
- **Electric Vehicle (EV)**
# Hybrid Power train Topology

![Hybrid Power train Topology Diagram](image)

## Degrees of Hybridization

### The vehicle is a...

<table>
<thead>
<tr>
<th>If it...</th>
<th>Micro Hybrid</th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
<th>Plug-in Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatically stops/starts the engine in stop-and-go traffic</td>
<td>![Micro Hybrid icon]</td>
<td>![Mild Hybrid icon]</td>
<td>![Full Hybrid icon]</td>
<td>![Plug-in Hybrid icon]</td>
</tr>
<tr>
<td>Uses regenerative braking and operates above 60 volts</td>
<td>![Micro Hybrid icon]</td>
<td>![Mild Hybrid icon]</td>
<td>![Full Hybrid icon]</td>
<td>![Plug-in Hybrid icon]</td>
</tr>
<tr>
<td>Uses an electric motor to assist a combustion engine</td>
<td>![Micro Hybrid icon]</td>
<td>![Mild Hybrid icon]</td>
<td>![Full Hybrid icon]</td>
<td>![Plug-in Hybrid icon]</td>
</tr>
<tr>
<td>Can drive at times using only the electric motor</td>
<td>![Micro Hybrid icon]</td>
<td>![Mild Hybrid icon]</td>
<td>![Full Hybrid icon]</td>
<td>![Plug-in Hybrid icon]</td>
</tr>
<tr>
<td>Recharges batteries from a wall outlet for extended all-electric range</td>
<td>![Micro Hybrid icon]</td>
<td>![Mild Hybrid icon]</td>
<td>![Full Hybrid icon]</td>
<td>![Plug-in Hybrid icon]</td>
</tr>
</tbody>
</table>

### Function

<table>
<thead>
<tr>
<th>Function</th>
<th>Micro Hybrid</th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
<th>Plug-in Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel economy</td>
<td>5% to 10%</td>
<td>7% to 15%</td>
<td>&gt;30%</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Power levels</td>
<td>3kW to 5kW</td>
<td>10kW to 15kW</td>
<td>&gt;20kW</td>
<td>&gt;20kW</td>
</tr>
</tbody>
</table>

48/12 Volt Architectures (Micro and Mild Hybrids)

- There are 2 basic Architectures for 48/12 Volt Systems, which can be functionally identical within the power range of an accessory belt drive
  - Belt Driven Alternator-Starter
    - Advantageous when other powertrains are used on the same vehicle since the basic engine & transmission configuration is common.
  - Integrated Starter-Alternator
    - Does not have large starter-alternator external to the powertrain
    - Can transmit more power since it is not limited by belt drive.
    - Packaging tradeoff at the expense of serviceability

Series Hybrid Vehicles

- Uses two Machines: generator and motor
- Generator sized for continuous power of vehicle
- Motor sized for peak power of vehicle
- All power must flow from engine through generator and motor to drive wheels

Advantages:
- Flexibility of location of engine-generator (e-g) set
- Simplicity of drivetrain
- Suitable for short trips

Disadvantages:
- Needs 3 propulsion components (ICE, Generator and Motor)
- Motors must be designed for maximum sustained power, $P$
- All 3 drivetrain components need to be sized for long distance-sustained, high-speed driving

The electric motor provides all the propulsion power
Parallel HEV

- A parallel hybrid is an HEV in which more than one energy converter can provide propulsion power
- Uses one machine for motor and one for generator functions
- Motor sized for a fraction of peak vehicle power
- Power flows from engine directly through transmission to drive wheels

Both the ICE and the electric motor are connected to the driveshaft

- **Advantages**
  - Smaller engine or motor can produce the same performance

- **Disadvantages**
  - Control complexity
  - Power blending from the ICE and motor necessitates a complex mechanical device

Series-Parallel Combination HEV

- Uses two Machines: generator and motor
- Motor and generator are sized for fraction of peak vehicle power
- Provides both series and parallel path from engine to drive wheels
- A small series element + parallel HEV (Ex: Toyota Prius)
- IC engine is also used to charge the battery
- Electric motor delivers power to the front wheel in parallel with the ICE
- Inverter is bi-directional: Charging batteries and providing power to motor
- Central control unit regulates the power flow
Toyota Hybrid System II
With two-stage motor speed reduction device

PRIUS OPERATION

1. Starting or moving under very low load
2. Normal driving
PRIUS OPERATION

Honda Intelligent Multi-Mode Drive (iMMD)

<table>
<thead>
<tr>
<th>EV Drive</th>
<th>Hybrid Drive</th>
<th>Engine Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use electric energy from battery to drive motor</td>
<td>Use electric energy from engine generator to drive motor, with assistance from battery</td>
<td>Use engine to directly drive wheels</td>
</tr>
</tbody>
</table>

- Electrical Transfer
- Mechanical Transfer
Plug-in Hybrid Vehicle

- All-electric range
  - Get home with exactly no battery charge left
- Charge-sustaining mode

![Diagram of battery charge levels and distance traveled.](image)

[Tate, Harpster, and Savagian 2008]

### 2017 Chevrolet Volt Plug-in Hybrid

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>87 kW PM Motor, 48kW ferrite motor</td>
</tr>
<tr>
<td>Torque</td>
<td>294 lb-ft</td>
</tr>
<tr>
<td>EPA MPG (City/Highway/Combined)</td>
<td>43/42/42</td>
</tr>
<tr>
<td>MPGe</td>
<td>106 miles</td>
</tr>
<tr>
<td>Range Electric/Overall</td>
<td>53 miles/420 miles</td>
</tr>
<tr>
<td>Battery Type</td>
<td>Li ion</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>18.4kWh, 300V</td>
</tr>
<tr>
<td>Charging time @ 120V</td>
<td>13hrs</td>
</tr>
<tr>
<td>Charging time @ 240V</td>
<td>4.5hrs</td>
</tr>
<tr>
<td>Curb weight</td>
<td>3543 lbs</td>
</tr>
</tbody>
</table>

In EV driving, the 2 motors can be linked together so the total power is actually higher than the original Volt which allows the 2016 Volt to accelerate from 0-30 mph in a very aggressive 2.6 seconds.
### 2017 Toyota Prius Plug-In Hybrid

<table>
<thead>
<tr>
<th>Horsepower, 1.8L engine (EV/ECO/Power)</th>
<th>95 HP @5200rpm</th>
<th>System net power</th>
<th>121 HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>105 lb-ft</td>
<td>Motor type</td>
<td>PMSM</td>
</tr>
<tr>
<td>Curb weight</td>
<td>3365lb</td>
<td>Voltage</td>
<td>600V(max)</td>
</tr>
<tr>
<td>Acceleration 0-62mph</td>
<td>10.7secs</td>
<td>Battery voltage</td>
<td>351.5V</td>
</tr>
<tr>
<td>Top speed electric/combined</td>
<td>62mph / 112mph</td>
<td>Battery capacity</td>
<td>8.8kWh</td>
</tr>
<tr>
<td>Range (electric/total)</td>
<td>25miles / 640miles</td>
<td>EPA MPG (city/high/combined)</td>
<td>55/53/54</td>
</tr>
<tr>
<td>Battery charging time 240V</td>
<td>2hrs 10min</td>
<td>Battery charging time standard</td>
<td>5hrs 30mins</td>
</tr>
<tr>
<td>Battery Type</td>
<td>Li-ion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2020 Mitsubishi Outlander PHEV-2020

Motor: Twin AC Synchronous permanent magnet motor:141.7 kW

<table>
<thead>
<tr>
<th>Motor Torque output</th>
<th>195Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>12kWhr Li-ion - 300 V</td>
</tr>
<tr>
<td>Engine</td>
<td>117HP @4,500rpm, 2 L</td>
</tr>
<tr>
<td>Pure EV range</td>
<td>22 miles</td>
</tr>
<tr>
<td>Total range</td>
<td>310 miles</td>
</tr>
</tbody>
</table>
2021 Toyota Mirai Fuel Cell Vehicle

Toyota hydrogen fuel cell car Mirai.
Base Price: $49,500
Range: 650 km
Trunk can hold 5.6 kilograms of hydrogen when compressed at 10,000 psi
Lithium ion battery: 310.8V and 4.0 Ah,
Motor: 182-hp/221 lb-ft Permanent-magnet motor
Range: 404 miles


Electric Vehicle Charging
Electric Vehicle Charging

Conductive Charging

Inductive charging

To charge, an EV has to be simply parked or driven over a pad

Structure of electric vehicle battery charging system
DC Fast Charging

- DC-fast charging (DCFC) enables a direct connection to the DC leads to the vehicle battery for the very fastest rate charging.
- DCFC is most often associated with the fastest charging rates possible in an attempt to approach the rapid energy transfer rate of gasoline refueling.
- DCFC charge rates of 100kW+ require grid connections that are only typically available in commercial or industrial sites (and not homes).
- For an intercity trip, a rough estimate is that a large battery BEV (such as an 85kWh Tesla Model S) can acquire enough charge for about 2.5 hours of highway driving in 30 minutes at the fastest Tesla Supercharger DCFC station.
- Siemens has developed a 150kW charger with up to 920V capability.
- Automobile manufacturers are launching long-distance battery-powered vehicles worldwide, which can recharge a range of 500 km in 10 to 15 minutes (Charging like refueling)

Bi-directional on-board charger (V2G and G2V)

Bel Power Solutions has introduced the a 22/25 kW bi-directional liquid-cooled on-board inverter battery charger with export functionality. Up to 4 of these charging units can be connected in parallel, with efficiency near 94%.

It is possible to connect this charger to a charging station or directly to the grid (190-264 VAC single-phase or 330-528 VAC three-phase) to charge EV batteries. The output voltage covers a wide variety of batteries from 240 VDC to 800 VDC, with a constant 60-amp output current. When running on battery power, the system can export up to 25 kW (400 VAC @ 50 Hz or 480 VAC @ 60 Hz) to power three-phase AC equipment.
An inductive power wireless (IPT) transfer uses strongly coupled magnetic resonance to transfer power from a transmitting on the ground to the receiving pad in the EV.
Electric Motors for EV/HEVs

- Motor determines the characteristics of the drive system and the controller, and also it determines the ratings of the power devices of the inverter. Types of motors considered for EV/HEVs are:
  - Three phase induction motor
  - Permanent magnet synchronous motor
    - Surface mount motor
    - Interior PM motor
    - Concentrated winding motor
  - Switched Reluctance Motor
  - Synchronous Reluctance Motors

Power Electronics

- Power electronics and high power density electric machines are the enabling technologies for the successful development of MEAs. Further work is needed in the following areas:
  - Power device packaging required to withstand the large temperature variations, and high thermal cycle capability
  - Effects of EMI, and EMI mitigation at high altitudes
  - Fault tolerant power conversion topologies
  - High temperature operation of power electronics and electric machines (For embedded generation, up to 250°C)
  - Passive components with reduced weight, volume, and high temperature capability

- **Wide band gap devices (SiC and GaN) can meet some of the challenges:**
  1. Reduced heat-sinking / thermal management
  2. Closer integration into the hostile engine environment
  3. Reduced passives with increased switching frequency
  4. Alternative circuit topologies with inherently reduced passives

- Several companies have developed inverter prototypes based on SiC switches that show significant size reduction up to 1/6 of the size with silicon devices
Integrated Motor and Inverter

The Integral e-Drive division of Integral Powertrain has collaborated with McLaren Applied Technologies and Hewland Engineering to design a new electric axle system. The e-axle features integrated inverter technology from McLaren, two 200 kW permanent magnet motors from Integral e-Drive, and two reduction gear sets for torque vectoring from Hewland. Overall power density is 4.4 kW/kg

BorgWarner to build integrated drive module for Ford Mustang Mach-E


Battery characteristics

• The main considerations in the selection of EV/HEV batteries are
  * Power density
  * Energy density
  * Weight
  * Volume
  * Cycle life
  * Temperature range
  * Environmental conditions
  * Cost

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Lead acid</th>
<th>NiMH</th>
<th>Lithium-ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Density (Wh/kg)</td>
<td>30-40</td>
<td>50-80</td>
<td>100-160</td>
</tr>
<tr>
<td>Power density (W/kg)</td>
<td>120-200</td>
<td>250-1000</td>
<td>1000-1500</td>
</tr>
<tr>
<td>Cycle life</td>
<td>200-300</td>
<td>300-500</td>
<td>500-1000</td>
</tr>
</tbody>
</table>
Lithium ion batteries

Li-ion systems get their name from their unique cathode materials. The lithium-ion family is divided into three major battery types, so named by their cathode oxides, which are cobalt, manganese and phosphate. The characteristics of these Li-ion systems are as follows.

- **Lithium-ion-cobalt** or **lithium-cobalt** (LiCoO2): Has high specific energy with moderate load capabilities and modest service life. Applications include cell phones, laptops, digital cameras and wearable products.
- **Lithium-ion-manganese** or **lithium-manganese** (LiMn2O4): Is capable of high charge and discharge currents but has low specific energy and modest service life; used for power tools, medical instruments and electric powertrains.
- **Lithium-ion-phosphate** or **lithium-phosphate** (LiFePO4): Is similar to lithium-manganese; nominal voltage is 3.3V/cell; offers long cycle life, has a good safe record but exhibits higher self-discharge than other Li-ion systems.

Solid state batteries

- Solid-state batteries replace the liquid or polymer electrolyte found in current lithium-ion batteries with a solid.
- The key difference between the commonly used lithium-ion battery and a solid-state battery is that the former uses a liquid electrolytic solution to regulate the flow of current, while solid-state batteries opt for a solid electrolyte. A battery’s electrolyte is a conductive chemical mixture that allows the flow of current between the anode and cathode.
- Solid state batteries still work in the same way as current batteries do, but the change in materials alters some of the battery’s attributes, including maximum storage capacity, charging times, size, and safety.
- The main benefits are batteries that are lightweight, smaller, higher-capacity and cheaper than current liquid-based lithium-ion batteries.
- Solid state Batteries are becoming increasingly relevant with the adoption of electric vehicles. Toyota and Dyson both believe solid-state batteries could be in final products in the very near future.
**EETT Roadmap**

Electrical and Electronics Technical Team Roadmap Roadmap October 2017

Future Vehicles

- MOSFET-IGBT - Silicon carbide based vehicles
- Advanced high density packaging and operating at junction 250°C temperature and up to 100kHz
- Induction- PM - Synchronous Reluctance?
- Presently, no standards for nominal battery voltage. In future, there will be standards based on the classification of the vehicles
- Lead acid- NIMH- Lithium ion- Solid state- Lithium Air (Long term ?)
- Wireless Charging
- Renewable energy for charging
- Grid integration: Most new electric vehicles come with grid power connection as standard
- Driverless-Autonomous-connected
- 3D printing, packaging, and miniaturization
- New materials and processes
- Flying cars and VTOL vehicle

Questions?