ELECTRIC VEHICLES: ARCHITECTURE

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References

- Le véhicule électrique. Educauto. www.educauto.org
Outline

- Introduction
  - History
  - Electric powertrain of road vehicles
  - Electric powertrain in railway vehicles

- Architectures of electric powertrains
  - Centralized electric drivetrain
  - Distributed electric drivetrain
  - Hybrid
Outline

Electric machines:
- Types and properties
  - DC machines
    - Series, shunt, independent excitation
  - AC machines
    - Induction machine
  - Synchronous machine with permanent magnets
  - Switched reluctance machines (SR)
- Performance and sizing

Electronic power converters
- Choppers
- Inverters
Outline

- Energy accumulators
  - Batteries
    - Characteristics and operating variables
    - Types
    - Comparison
  - Super capacitors
  - Flywheels
Introduction
Between 1832 and 1839 (the exact year is uncertain), Robert Anderson of Scotland invented the first crude electric carriage.

A small-scale electric car was designed by Professor Stratingh of Groningen, Holland, and built by his assistant Christopher Becker in 1835.

Practical and more successful electric road vehicles were invented by both American Thomas Davenport and Scotsmen Robert Davidson around 1842. Both inventors were the first to use non-rechargeable electric cells.
History – Electric car

- Frenchmen Gaston Plante invented a better storage battery in 1865 and his fellow countrymen Camille Faure improved the storage battery in 1881. This improved-capacity storage battery paved the way for electric vehicles to flourish.

- 1890 – 1910 – Period of significant improvements in battery technology, specifically with development of the modern lead-acid battery by H. Tudor and nickel-iron battery by Edison and Junger.

- Electric vehicles would hold all vehicle land speed records until about 1900.
History – Electric car

1899: The first car to break the 100 km/h (105,88 km/h) is an electric car: The «Jamais contente» was driven by its Belgian inventor Camille Jenatzy. The car is made of partinium (an laminated aluminum alloy) while its aerodynamics is inspired by torpedoes.
History – Electric car

- The electric car exists from the eve of automobile in the end of 19th century

- After some erratic period that end up in the 30ies, the piston engine has definitively won the contest and has been since that time the dominating solution for road vehicles

- Electric machines has intrinsically superior characteristics superior to piston engines:
  - Constant power in a large range of operation
  - No idle regime
  - Easy maintenance
  - Reliability
History – Electric car

- However the energy storage system based on batteries appears to be less efficient than petrol that was abundant and cheap:
  - Higher specific energy so longer range and autonomy
  - Easiness of maintenance
  - Not expensive
  - Abundant

- Nowadays, one might have believed that electric drivetrain was forgotten for ever, piston engine is the victim of its success story:
  - Reduction of petrol resources
  - \( \text{CO}_2 \) emissions
  - Emissions of pollutants from combustion
History – Electric car

- In the beginning of the 21st century, the electric motor could be the final winner.

- Indeed, in order to preserve individual mobility, one needs vehicles with:
  - Less pollutants
  - Less noise
  - Less fuel consumption
Electric traction for railway vehicle is born in the beginning of the 20th century for underground railways in order to substitute to steam engines used in locomotives.

The electric traction for railways develops in the 20th century and expands in the middle of the 20th century. Steam locos are replaced by:
- Electric locos (in major part of Europe and Africa)
- Diesel locos (in the USA for instance)
History – Railway vehicle

- With the first oil crisis in 1973, the electric traction systems become dominant in Europe
  - For instance, the French TGV that was initially designed with a gas turbine is equipped with electric machines
History – Railway vehicle

- The Electric traction supersedes the steam engine in railway transports because:
  - Smaller operating cost
  - Higher available power
  - Higher rotation speed
  - Easiness of operation:
    - No refueling for water and coal
    - No preparation (warming) period before operation
  - When electrical power is supplied through the network, the autonomy has no limit
The major difficulty for electric railway in Europe is the large diversity of electrification systems (AC / DC, voltage, frequency):

- 1500 V DC (Pays Bas, South France)
- 3000 V DC (Belgium, Italy, Spain, Poland, CEI)
- 25.000 V AC @ 50 Hz (France, Denmark)
- 15.000 V AC @ 16 2/3 Hz (Germany, Switzerland, Sweden)

Because of various electrification systems, electric locos have to be equipped with machines /electronics able to work with twin (or triple) current systems.

The problem origin is coming from historical reasons. Modern tendency is to use standard AC current: 25 kV @ 50 Hz (industrial frequency)
Electrification systems in Europe
Source: wikipedia
### Percentage of electrification around the world

<table>
<thead>
<tr>
<th>Railway</th>
<th>Percentage Electrified</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.A.</td>
<td>0.9%</td>
</tr>
<tr>
<td>Canada</td>
<td>0.1%</td>
</tr>
<tr>
<td>Australia</td>
<td>9.6%</td>
</tr>
<tr>
<td>China</td>
<td>15.6%</td>
</tr>
<tr>
<td><strong>France</strong></td>
<td><strong>44%</strong></td>
</tr>
<tr>
<td>India (BG)</td>
<td>44%</td>
</tr>
<tr>
<td>Italy</td>
<td>59%</td>
</tr>
<tr>
<td>Sweden</td>
<td>59%</td>
</tr>
<tr>
<td>Austria</td>
<td>59%</td>
</tr>
<tr>
<td>Amtrack (USA)</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Source: Rail Business Report, 1999*
86000 Diesel Locomotives

- Rest of the World (42%)
- North America (26%)
- Europea
n Union (13%)
- China (10%)
- India (5%)
- Latin America (4%)

27000 Electric Locomotives

- Rest of the world (47%)
- Europea
n Union (32%)
- North America (0%)
- Latin America (1%)
- China (10%)
- India (10%)

Population of Diesel Locos in the World is 3.2 times that of the Electric locomotives (Source: World Bank Railway Database 2000)
History – Railway vehicle

COST OF OPERATIONS - ELECTRIC

Fixed(I&D)+Energy+I&D costs of locos
+ maintenance of -locos and OHE

Fixed(I&D)+Energy+(I&D)costs of
locos

Fixed(I&D)+Energy Cost

Fixed Costs - Interest and depreciation (I&D)
on the cost of installation.
History – Railway vehicle

COST OF OPERATIONS - DIESEL

Fuel+I&D costs of locos  
+Maintenance Cost of locos

Fuel+(I&D)cost of locos

No fixed Cost  
(Interest on cost of installation)

Fuel Cost

Diesel locomotives
History – Railway vehicle

CONCEPT OF BREAK EVEN POINT

COST OF OPERATIONS

TRAFFIC DENSITY - GROSS MILLION TONNES PER ANNUM

Diesel

Electric

Break even point

Fixed Cost for electric traction

12.5.2001
Electric Powertrain Architecture
Electric Powertrain

- Basic electric traction architecture usually mounted on light and heavy vehicles, as well as industrial (fork lifters, airfield vehicles...) and two wheelers

Energy source: batteries or network

Electronic management unit

Electric machine

Wheels and drivetrain
A modern electric drive is conceptually more complicated.

It is made of 3 subsystems
- Electric motor propulsion
- Energy source
- Auxiliary
Electric Powertrain

- Electric propulsion system
  - Vehicle controller
  - Power electronic converter
  - Electric motor
  - Mechanical Transmission
  - Driving wheels

- Energy source subsystem
  - Energy source or storage
  - Energy management unit
  - Energy refueling unit

- Auxiliary
  - Power steering
  - Hotel climate control
  - Auxiliary supply unit
Electric powertrain components

- **Electric machine:**
  - Converting electric energy into mechanical energy (motor regime) and vice versa (generator regime)
  - Types of electric machines
    - DC shunt or series or separately excited
    - AC synchronous
    - AC induction machines; 1 phase or 3 phase machines
    - Switched Reluctance Machine

- **Power electronics**
  - Modulation of power, speed, torque
  - Control of machine mode (motor, generator)
  - Types
    - Chopper, DC / DC converters, etc.
    - Inverter
Electric powertrain components

- Batteries:
  - Storing electric energy
    - Power source
    - Peak power source
  - Types
    - Lead-acid,
    - Nickel – Cadmium,
    - Ni – MH (metal hydride),
    - Li ions
    - Super capacitors
    - Flywheels
Electric powertrain components

- Transmission (mechanical)
  - Gear box
  - Differential
  - Wheels
One can distinguish 2 different solutions:

- **Centralized motorization**: similar to ICE configuration = one single motor and the power is transmitted to the wheels via a transmission line including gear boxes, transfer boxes, differentials, shafts.

- **Decentralized motorization**: electric motors are located on each wheels or close to each wheel sets (boogie).
  - On can further distinguished motors actuating the shaft or using direct drive technique
Electric powertrain architectures
Centralized motorization

- Similar concept to ICE engine
- May be not adapted to modern electric motorization
Decentralized motorization
Need for a gear box and a clutch?

- For piston engines (ICE), the gear box + clutch are necessary because of the unfavorable speed-torque of the engine

Typical drivetrain architecture with an ICE propulsion system
Need for a gear box and a clutch?

- In a naïve conversion of ICE cars to electric, one keeps the gear box and may be the clutch.
- However electric machines have
  - No idle speed
  - Large range of operating speed (0 to 3,000 rpm - 12,000 rpm)
  - Electronic controllers can regulate torque and speed easily
  - Rotation speed can be inverted

- Electric drivetrain can be equipped with a simple gear box: one or two gear ratios
Need for a gear box and a clutch?
Need for a gear box and a clutch?

- Advantages of fixed ratio gear box:
  - No shocks during operations. Smooth drive.
  - Planetary gear ratio can achieve important reduction ratios in a single stage with a good efficiency

- Cost of electric motor strongly depends on the maximum torque:
  - Using a high speed motor is favorable to reduce the cost
  - But the acceleration factor is affected by high gear ratio

- Selection of single or multiple gear ratios depending on:
  - Acceleration requirements
  - Max slope and max drawbar pull requirements
  - Speed range of the motor
Unique or multiple motors configuration?

- The unique motor configuration is typical from ICE.

- With electric motor, one can imagine more innovative designs and it is possible to actuate each degrees of freedom independently as in robotics and mechatronic systems.

- With distributed motorization with multiple motors, one can even abandon the concept of a differential and replace it by 2 or 4 motors, one per each wheel.

- The mechanical differential is replaced by an electronic differential systems with control loop.
Multiple motors configurations

(c) motoréducteur répartis (S3)
(d) entrainement direct par moteurs intégrés dans les roues (S4)
Unique or multiple motor configuration?

- Advantages of multiple motor configurations
  - Reduction of the weight and volume constraints
  - Electronic differential system opens new possibilities to control torque and speed difference at each individual wheels
  - New possibilities in controlling the vehicle dynamics:
    - Longitudinal dynamics: antiskid and anti lock braking (ABS) systems
    - Lateral dynamics: extended electronic stability program, torque vectoring

- Inconvenient
  - Using additional electronic systems
  - Reliability of the overall system?
  - Additional cost
  - Increasing system complexity
In-wheel motor concept

- The concept of in-wheel motors reduces to a minimum or completely avoids the mechanical transmissions by placing directly the motors inside the wheels.
- One distinguishes:
  - **Inner in-wheel motors** whose rotation speed is rather high and is reduced using a fixed gear ratio.
  - **Outer in-wheel motors** whose rotation speed is low and that are connected in direct-drive.
- Both approaches generally use permanent magnet (PM) motors because of their high specific power.
Inner in-wheel motor
Outer in-wheel motor
In-wheel motor concept

- The inner in-wheel motor
  - The max rotation speed is rather high (for instance 10 000 rpm)
  - Requires a gear box (about 10:1) for instance a planetary gear mounted on the wheel hub
  - Smaller size and smaller weight
  - Smaller cost

- The outer in-wheel motors
  - Simplicity of the concept
  - No reduction of speed nor gear box
  - Larger sizes and higher weight: might have some impact on comfort and road holding
  - High cost
In-wheel motor concept

Motor wheel specifications in brief
(other versions are available)
Peak Power  80 kW  107 hp
Nominal Power: @950rpm 18.5kW (25hp)
Peak torque  670 Nm  494 lb ft
Nominal torque @ 950 rpm  180 Nm  
(133lbft)
Peak speed:  1385 rpm
Max continuous speed:  1235 rpm
Efficiency under continuous load @
950rpm  \( \eta = 96.3 \% \)
Maximum supply voltage  500 VDC

In-wheel motor from TM4
In-wheel motor concept

MIEV Lancer Evolution equipped by 4 in-wheel motors
In-wheel motor concept

MIEV Lancer Evolution equipped by 4 in-wheel motors

<table>
<thead>
<tr>
<th>Motor (outer-rotor type)</th>
<th>Type</th>
<th>Permanent magnetic synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maker</td>
<td>Toyo Denki Seizo K.K.</td>
<td></td>
</tr>
<tr>
<td>Max. output</td>
<td>50 kW</td>
<td></td>
</tr>
<tr>
<td>Max. torque</td>
<td>518 Nm</td>
<td></td>
</tr>
<tr>
<td>Max. speed</td>
<td>1500 rpm</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>445 mm (dia.) x 134 mm</td>
<td></td>
</tr>
<tr>
<td>No. fitted</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
In-wheel motor concept

MIEV Lancer Evolution equipped by 4 in-wheel motors
In-wheel motor concept

The V-Flow system. Vertical gas flow, vertebral layout, volume-efficient. Note the cutaway of the rear wheel showing the in-wheel motor.

In-wheel motor 25 kW

Honda FCX powered by a fuel cell
In-wheels motor concept

- Bike applications:

www.acclivity.ca

www.smart-bike.net
Other electric powertrains

- **TWO MODE TRACTION or PARALLEL HYBRID**
  - The ICE powertrain is used outside of the cities while electric powertrain is more efficient for urban driving.

Diagram:
- Turbine or ICE
- Batteries
- Electronic control unit
- Electric machine
- Transfer box
- Wheels
Other electric powertrains

- **SERIE ELECTRIC POWERTRAIN**
  - The ICE (piston engine or gas turbine) is used to power a generator that feeds in continuous batteries.
  - The batteries supplies the electric motor that is the only one to be connected to the wheels.
Electric powertain for road vehicles

- Advantages:
  - Zero emissions on site → urban application
  - Zero (low) noise emissions
  - Simple mechanical transmission (no gear box)
  - Torque and speed regulation possible
  - Energy recovery while braking
  - High torque at low and zero speed
  - Smooth operation
  - No range limitation if external power supply (catenaries for trains)

- Disadvantages:
  - Weight penalty and cost of batteries
  - Limited autonomy is batteries (Max 200 km)
## Typical characteristics for electric vehicles

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Max power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric bike</td>
<td>100 – 400 W</td>
</tr>
<tr>
<td>Scooter</td>
<td>2 kW</td>
</tr>
<tr>
<td>Sport motorcycle</td>
<td>14 to 25 kW</td>
</tr>
<tr>
<td>Kart</td>
<td>8 kW</td>
</tr>
<tr>
<td>Urban car</td>
<td>20 to 40 kW</td>
</tr>
<tr>
<td>Intercity car</td>
<td>50 to 70 kW</td>
</tr>
<tr>
<td>Urban utility vehicle</td>
<td>40 kW</td>
</tr>
<tr>
<td>Urban bus</td>
<td>160 kW</td>
</tr>
</tbody>
</table>
Typical characteristics for electric vehicles

- Pure electric car (m=1200 kg)
  - $P_{IC} = 0$ kW
  - $P_{elec} = 75$ kW
  - $V = 300 – 500$ V

- Series hybrid vehicle (m=1373 kg)
  - $P_{IC} = 41$ kW
  - $P_{elec} = 75$ kW
  - $V = 300 – 500$ V

- Parallel hybrid vehicle (m=1330 kg)
  - $P_{IC} = 50 - 60$ kW
  - $P_{elec} = 30 - 50$ kW
  - $V = 300 – 500$ V
Typical characteristics for electric vehicles

- Parallel hybrid bus (m=16 800 kg)
  - $P_{IC} = 170$ kW
  - $P_{elec} = 190$ kW
  - $V = 600$ V

7900 Volvo Plugin Hybrid Charging at Redbergsplatsen in Gothenburg