Electrification of transportation:
Overview of the latest technical and market developments in e-mobility in North America and beyond

Bruno Lequesne
Consultant, E-Motors Consulting, LLC
bruno.lequesne@ieee.org
www.emotorseng.com

CWIEME
October 1, 2014
Who I am

• Electrical engineer, motors and electromagnetic expert, with 30 years of experience for automotive and transportation applications
  • GM Research, Delphi Research, Delphi Powertrain, Eaton
  • Worked on valvetrain electrification, power steering, electric brakes, throttle control, sensors, starter-generators and hybrid systems, etc.
  • 50 patents, number of publications in IEEE and SAE journals and conferences

• Now a consultant
Overview

• Introduction: Why automobile electrification?

• The less visible groundswell: The “not hybrid” story
  • Chassis and powertrain electrification

• The visible part: Hybrids and electric vehicles

• Impact on electric machine technology

• Market perspective and challenges ahead
Automotive electrification: Motivations

- Long history on gas-powered vehicles:
  - Starter motor (1911)
  - Radio (1950’s)
  - Currently, some 30 motors per car
    - Mostly simple, low cost brushtype

- Motivation is very diverse:
  - Energy efficiency is only one factor
  - Reduced emissions
    - Smaller engine size with hybrids
  - Convenience and features:
    - Many gadgets require power or actuators
  - Performance
  - Image

- Key enablers:
  - Power electronics
  - Computer and controls

Kettering demonstrating starter on a Buick (1913)

Source: ohiohistorycentral.org
Overview

• Introduction: Why automobile electrification?

• The less visible groundswell: The “not hybrid” story
  • Chassis and powertrain electrification

• The visible part: Hybrids and electric vehicles

• Impact on electric machine technology

• Market perspective and challenges ahead
Chassis electrification

- Chassis: Trilogy of steering, brake, suspension -> Vehicle handling

- All 3 can be electrified
  - Power steering: For fuel economy
  - Suspension: For variable suspension rates
  - Brakes: To eliminate brake fluids, and improve response time
  - All 3 for improved controllability

Image: melexis.com
**Electric power steering (EPS)**

**Motivation:**
- Fuel economy, power on demand
- Hydraulic power steering requires the pump to be on all the time, a 1 mile/gallon penalty

**History:**
- Introduced on Susuki (1988), small Fiat car in 1999
- Becoming standard on passenger vehicles

**Issues:**
- Torque ripple (can be felt by driver)
- Need for fail safe features
- Cost:
  - Need for EPS to be almost on par with hydraulics
Electric power steering: Low torque ripple

- **Approach:**
  - Synchronous PM motor have no torque ripple
  - There are known ways to eliminate cogging:
    - Slot/pole combinations
    - Skew
    - Phantom slots

- **When theory meets practice:**
  - Manufacturing variations are critical!
  - Magnet magnetization pattern
  - Eccentricity
  - Required:
    - In-depth detailed understanding of impact of all variations on torque
    - Proper design: Six Sigma, Taguchi methods
    - Proper manufacturing

![Cogging torque vs. magnet misplacement](Source: Nexteer.com)

Islam, et. al. (Delphi/Nexteer)  
*T. Indus. Appl., 2004*
Variable-rate suspensions

• Issues:
  • Conventional suspension have a fixed damping rate versus frequency
  • Accommodate various comfort levels: Plush versus sporty

• Solution #1:
  • Magnetorheological fluids: Oil filled with iron particles
  • Oil viscosity varies with applied magnetic field
  • Developed by GM/Delphi/Lord
  • Used on luxury vehicles: Cadillac, Corvette, Lexus, Ferrari

• Development hurdle:
  • Proper material with low sedimentation rate

• Limitation:
  • Only semi-active damping
Active suspension systems

• Linear motors (Bose, etc)

• Motor with ballscrew-ballnut (GM)

• Advantages:
  • 100% controllable ride
  • Very minor energy harvesting

• Issues:
  • Size, energy consumption, cost

Source: Hao, et. al, (GM) IEEE ECCE Conf. 2011

Source: techeblog.com
Powertrain electrification

- Engines are no more mechanical...

- Electronic throttle control (Delphi)
- Fuel injector (Bosch)
- Electric water and oil pumps (BMW, Alfa-Romeo)
- Electric cam phaser (Delphi)
- Engine controller (Delphi)
- Starter-generator (Denso)

Engine image: rouschperformance.com
Throttle-by-wire

- Gas pedal system:
  - Linked to throttle by electric wires
  - Mechanical linkage disappeared 15 years ago

- Advantage:
  - Can manage input from driver AND steering, braking, etc (ABS system)
  - Less wear

- What about safety?
  - Toyota recall (2009)...
  - Electronic systems safer than mechanical systems
    - Redundancy
    - Sensors as fault observers
    - Fewer components, less wear
    - Not subject to human failures
    - Contributes to ABS and other safety functions

Source: Toyota.com

Source: Delphi.com

Source: Melexis.com

Source: Melexis, ee-times.com
Fuel injectors – Faster, more precise

• Fuel injectors are just solenoids, right?
  • Fuel injectors led the development of FEA in linear motion (1980s)
  • Fuel injectors use piezo technology in mass production
• Why?
  • Move from carburetor to port to in-cylinder injection
  • Fuel dispersion and atomization key to clean burn
  • Precision and repeatability critical
  • Trend towards for multi injections per cycle

Source: howstuffworks.com

Source: atzonline.com

Source: marineinsight.com

Source: atzonline.com
Fuel injectors – Electromagnetic versus piezo

- Piezo injectors making in-roads despite of cost, size, need for high voltage
  - May be as long as 8”
  - Need for high voltage supply
  - Stack may be immersed in pressurized fuel

Not to scale!
Superchargers and turbochargers

- Engine downsizing by intake air pressurization
  - Significant fuel economy
  - Turbocharging: Powered by exhaust gas
  - Supercharging: Mechanical or electric actuation

- Example: Electric turbo compounding
  - Exhaust gas drives turbine to compress air
  - Electric motor mounted coaxially:
    - Drives system when exhaust pressure is low
    - Can generate power when plenty of exhaust pressure

Source: mts.com

Source: goapr.com

10/01/2014, Slide 15
Stop-start systems

- Stop-start = Engine off at idle
  - Can save up to 4% in fuel

- Two types:
  - Regular system with stronger starter motor
  - Belt-driven combined starter-generator

Source: Chen, Lequesne, Henry (Delphi), IEMDC 2001

Source: AC Delco Training (archives online)

Induction starter-generator

Source: green.autoblog.com
Stop-start systems or micro hybrid?

- Stop-start systems are also called micro hybrids
  - Depends on marketing strategy
    - GM calls it “eAssist” – Does not want to scare off traditional customers
    - Others taunt environmental friendliness (Peugeot’s “écologique”)
  - Stop-start becoming standard, starting with Europe

Source: Buick.com

Source: Peugeot.com
Overview

• Introduction: Why automobile electrification?

• The less visible groundswell: The “not hybrid” story
  • Chassis and powertrain electrification

• The visible part: Hybrids and electric vehicles

• Impact on electric machine technology

• Market perspective and challenges ahead
Performance of electrics/hybrid

- Performance of electric/hybrid cars is excellent – On par with traditional

- Some cars (Lexus, Acura for instance) are hybridized for performance, not fuel economy

Tesla:

- 248 hp (185 kW) motor
- 0–60 in 3.9 s

Source: Teslamotors.com

Lotus Elise:

- 163 kW supercharged engine
- 6-speed transmission
- 0-60 in 4.3 s

Source: Lotuscars.com
Hybrids: Performance advantage

- Electric motor and engine *complement* one another
  - Electric motors have strong torque at zero speed
  - Engine cannot start on their own, and require a transmission
Propulsion systems

- Electric vehicles and plug-in hybrids:
  - Electric system needs to meet most traction torque/speed points
- Hybrids:
  - Electric system simply aids the engine
  - Better defined as an electrified transmission?

Which is more complex?

Lexus 8-gear transmission  
Source: Wikipedia Commons

Toyota Prius
Propulsion and hybrid motors: Load cycle

- Importance of low-load points on overall efficiency

**Urban cycle**

**Highway cycle**

Max. torques (transient and continuous)

Actual operating points

Camry 2007 efficiency map

Source: Emadi, Trans. PEL, 2006

Where efficiency matters

Source: ORNL
Propulsion motors: Which motor type?

- **Permanent magnet:**
  - Favored for **hybrid vehicles:** Honda, Toyota, GM, Ford
  - Buried magnet design, with more and more reluctance torque
    - Less magnet material, better resistance to demagnetization

- **Induction:**
  - Favored for **all-electric** (GM EV1, Tesla)
    - Lower efficiency means range, can be offset with bigger battery
  - And **belt-driven**

*Source: ORNL reports*
What about switched reluctance?

- Used for heavy equipment
  - LeTourneau, all switched reluctance
  - John Deere: PM generator, SR motors
- Noise and vibrations of little concern
- Ruggedness and fault tolerance important

LeTourneau System

1 switched-reluctance generator
4 switched-reluctance wheel motors (300 kW)

Source: letourneau-inc.com and Emerson.com
Challenge: Cost

- DOE has established ambitious targets for cost and output
  - Requires more than just economies of scale

**Electric traction system**

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($/kW)</td>
<td>&lt; 12</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>Specific power (kW/kg)</td>
<td>&gt; 1.2</td>
<td>&gt; 1.4</td>
</tr>
<tr>
<td>Power density (kW/l)</td>
<td>&gt; 3.5</td>
<td>&gt; 4.0</td>
</tr>
<tr>
<td>Efficiency (10-100% speed at 20% tq.)</td>
<td>&gt; 93%</td>
<td>&gt; 94%</td>
</tr>
</tbody>
</table>

**Motor**

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($/kW)</td>
<td>&lt; 7.0</td>
<td>&lt; 4.7</td>
</tr>
<tr>
<td>Specific power (kW/kg)</td>
<td>&gt; 1.3</td>
<td>&gt; 1.6</td>
</tr>
<tr>
<td>Power density (kW/l)</td>
<td>&gt; 5.0</td>
<td>&gt; 5.7</td>
</tr>
</tbody>
</table>

DOE, 2007

Cumulative production (millions)

At 10,000 units
At 100,000 units
At 1,000,000 units

Cost estimates (2007)

Natural progression

Goals

10/01/2014, Slide 25
Overview

• Introduction: Why automobile electrification?

• The less visible groundswell: The “not hybrid” story
  • Chassis and powertrain electrification

• The visible part: Hybrids and electric vehicles

• Impact on electric machine technology

• Market perspective and challenges ahead
Impact on motor design: Examples

- Design for consistency:
  - Torque ripple, fuel injectors: Repeatability spec more critical than actual value
  - Taguchi method, design for 6 sigma

- Importance of design for load cycle (compound efficiency map)

- History of the modern generator as example of how to improve old technology competing with the new

- Motor construction and concentrated windings
Automotive generation

- Lundell alternator has reigned for 50 years:
  - Issues: Difficult to scale up, and low efficiency

DC generator

<table>
<thead>
<tr>
<th>Year</th>
<th>Lundell</th>
<th>Add permanent magnets (GM)</th>
<th>Windings as bars (Denso)</th>
<th>Water cooling (Bosch)</th>
<th>Active rectifier (Ford, MIT)</th>
<th>Twin rotors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>Lundell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990s</td>
<td></td>
<td>Add permanent magnets (GM)</td>
<td>Windings as bars (Denso)</td>
<td>Water cooling (Bosch)</td>
<td>Active rectifier (Ford, MIT)</td>
<td>Twin rotors</td>
</tr>
</tbody>
</table>

Speed (rpm)

- 0.6
- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
- 0

Output current (A)

- 0
- 1k
- 2k
- 3k
- 4k
- 5k
- 6k
- 7k
- 8k

Efficiency

Source: Ivankovic, et. al., New advances in vehicular..., InTech, 2002

Source: Nexteer.com
**Lundell improvements**

- **Permanent magnets in rotor**
  - Boosts rotor excitation field
  - Reduces leakage

Radomski (GM), US 4,959,577

- **Coil windings for better slot fill**

Umeda, et. al. (Denso), US 5,982,068
Lundell improvements

- Active rectifier
  - Lower losses (resistive drop better than diode voltage drop)
  - Control of phase angle

\[ P = \frac{3E}{X} \frac{V}{\sin \Theta} \]

- \( V \) is output voltage
- \( E \) is back-emf
- \( \Theta \) is angle (V,E)
- \( X \) is reactance

Liang, Miller, Xu (Ford), T. Ind. Appl., 1999
Motor construction

- Emergence of concentrated-coil windings
  - Obvious choice for flywheel-mounted motors
  - Simpler construction, better fill factor
  - Development of segmented stators

(Source ORNL report on motor technologies, 2011)

Honda Accord

(Source movingmagnet.com)

Fractional hp motor

Honda Insight

Full integration/modularity

(Brown, Jahns, Lorenz, IAM 2007)
Future needs

- Higher speed motors
  - Needs advances in motor and gear technology
- Thermal / Electromagnetic modeling integration
- Modularity
  - Especially non-automotive, to increase volume
- Higher temperature power electronics (to reduce number of cooling loops) and motor
- Materials:
  - Cast copper rotor (Tesla)
  - Laminations
- Voltage: 48V come back?
Overview

- Introduction: Why automobile electrification?
- The less visible groundswell: The “not hybrid” story
  - Chassis and powertrain electrification
- The visible part: Hybrids and electric vehicles
- Impact on electric machine technology
- Market perspective and challenges ahead
Market penetration

- Electrification is a slow but unrelenting process:
  - Example, electric power steering:
    - Worldwide deployment will skyrocket 72% to 79M vehicles in 2018 from 46M in 2013 (NSK, 8/2014)
  - True across the board: Automotive, off-road, ships, more-electric aircraft, etc.

- Hybrids and EVs keep knocking at the door
  - Sales increasing steadily, with regular upticks in enthusiasm
  - But have not really reached a tipping point yet

![Market penetration chart](image)

Lequesne, Electrification Magazine, 2014
Sales of electric (EVs) and hybrid (HEVs) vehicles (US)

- Trend is up, but still a niche market

Source: Electric Drive Transportation Association

3.8% of total car sales

US numbers

Source: Electric Drive Transportation Association
World view

- Technology penetration world map shows large variations, mirroring incentives and the price of gas
- Gas and electric vehicles have a different economic model
  - Electric: High initial price, low energy cost
  - Gasoline: Opposite

Norway
Netherlands
California
US (incl. CA)
France
Japan
Sweden
Denmark
Austria
Germany
UK
China

International Council on Clean Transportation (ICCT), 2014
China: Will it drive the technology?

- Very strong government incentives
  - Pollution mitigation
  - Economic independence
  - Leapfrog engine technology, and master the future

Source: Fleetsandfuel.com
Source: chinae-vehicle.com
Where are we going?

- So many contradictory announcements

Harley-Davidson announces its first electric motorcycle, LiveWire

LA Times, June 2014

Eaton Discontinues Diesel-Electric Hybrid Trucks

Truckinfo.com, September 2014

Image?

Dollars and cents?
Trends (personal opinion)

- Electrification is real, but a slow process

- Hybridization will happen, but through the back door:
  - Stop-start systems
  - Move to 48V
  - Stop-start systems will “grow up” over time: brake energy recovery, vehicle launch

- Full hybrids and electric will remain niche for a long time
  - EVs face a fundamental problem with battery cost and charging time
    - 1 gal of gasoline is 120 MJ of energy - a 3 minute refill is 13 MW rate
    - HEVs have the cost and complexity of two powertrains

- Only China can truly accelerate the trend, if government stays steady
Work in progress!