Status Review of Advances in Hybrid Electric Vehicles

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PES 2014

St. John’s (MUN)
Reasons for electric and hybrid vehicles

Why EVs and HEVS?
Yaskawa IPM Motor

200/400 V 級  0.4 〜 3.7 kW
Presentation Outline

- Introduction
- IPM motor technology
  - Design
  - Starting
  - Operation
  - Applications
- Challenges
  - Create variation of d-q axis inductances without varying air gap
  - Vary and Control of excitation of permanently excited rotor of IPM
  - Optimum variation of PM torque and reluctance torque in IPM for specific applications
  - Reduction of cost, weight, size of IPM for specific applications
  - Intelligent power converter and inverter for IPM motor drives
Contents

- Requirements for hybrid electric vehicles
- History of high efficiency permanent magnet motor technology using non-rare earth (ferrites) and rare earth (NdBFe) permanent magnet materials
- Example #1 for uses of IPM Technology in compressors for air conditioners
- Example #2 for uses of IPM Technology in motors/generators for HEVs
History of Permanent Magnet Materials
Gasoline prices on the rise
Extensive fossil fuel use gradually diminishes world reserves
Energy Diversification

World Energy Consumption in 2012 (EIA Data)

World Transportation Energy by Source, 2009 (IEA data)

Energy Security
Environmental and ecological concerns

- Primary pollutants released from road vehicles are CO$_2$, NO$_x$ and particulate materials.
- Transportation is the largest end use source of greenhouse gases.
- Transportation contributed to 27% of total US greenhouse gas emissions in 2010.
- Net 45% increase in total US greenhouse gas emissions from 1990 to 2010.

Environmental Pollution
EV/HEV Growth

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2011</th>
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<tbody>
<tr>
<td>Vehicle Type</td>
<td>EV</td>
<td>HEV</td>
</tr>
<tr>
<td>USA</td>
<td>56,901</td>
<td>1,324,497</td>
</tr>
<tr>
<td>UK</td>
<td>1,405</td>
<td>47,035</td>
</tr>
<tr>
<td>Netherlands</td>
<td>60,452</td>
<td>20,005</td>
</tr>
<tr>
<td>France</td>
<td>N.A.</td>
<td>24,000</td>
</tr>
<tr>
<td>Denmark</td>
<td>10,600</td>
<td>300</td>
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EV sales includes E-bikes
**Rare earth problem**

Rare earth material cost has increased. In last 8 years, Nd and Dy prices are 17 and 36 times the price in 2005.

<table>
<thead>
<tr>
<th></th>
<th>Nd</th>
<th>Dy</th>
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<tbody>
<tr>
<td>2005</td>
<td>$10/kg</td>
<td>$50/kg</td>
</tr>
<tr>
<td>2010 April</td>
<td>$40/kg</td>
<td>$270/kg</td>
</tr>
<tr>
<td>2011 July</td>
<td>$500/kg</td>
<td>$3000/kg</td>
</tr>
<tr>
<td>2012 May</td>
<td>$170/kg</td>
<td>$1800/kg</td>
</tr>
<tr>
<td>last 8 years</td>
<td>17</td>
<td>36</td>
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</table>
Estimated Prius 09 motor material cost

PM occupies 64% and 81% in the total material cost in 2005 and 2012.

<table>
<thead>
<tr>
<th>item</th>
<th>2005 US$/kg</th>
<th>2012 US$/kg</th>
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<tbody>
<tr>
<td>Winding</td>
<td>8.75</td>
<td></td>
</tr>
<tr>
<td>Iron (0.35mm)</td>
<td>3.75</td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>625</td>
<td></td>
</tr>
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</table>

PM cost is $250/kg and $625/kg in 2005 and 2012, respectively.
Motivation of NEDO projects

- **Rare-Earth-Free electric motors** are strongly demanded for mass production HEVs and EVs.
- NEDO has started rare-earth-free or half-rare earth motor projects since 2008.
- The rare-earth-free motors must have
  1. **Competitive size**
  2. **Competitive power density**
  3. **Competitive efficiency**
  4. **but no rare-earth permanent magnet**

with respect to the rare-earth(NdFeB) IPM motors employed in HEVs and EVs. Thus, the targets are very challenging. Rare-earth-free motors are **a new generation motor** of post NeFeB IPM motors.
Summary of target specific NEDO projects for rare-earth-free motor

1. **Switched reluctance motor (TUS&TIT)**
   target: 2\textsuperscript{nd} generation Prius

4. **Ferrite PM axial gap motor with segmented rotor (Hokkaido Univ.)**
   target: 2\textsuperscript{nd} generation Prius

1. **Permanent magnet assisted synchronous reluctance motor with stepped gap**
   target: 2\textsuperscript{nd} generation Prius 1/10 scale

2. **Wound field winding and soft magnetic composite core motor**
   target: Lexus 400h
Target IPM motor analysis

Model Prius’ 03 flux density analysis

1200r/min, 400 Nm
Serious magnetic saturation
Max. current
Vdc is the maximum.
Max. inverter VA.

SPEED
PC-BDC+FEA
3000r/min, 50kW

- half of the rated current for 50kW
- field weakening $\beta=65\text{deg}$
- Magnetic saturation is not apparent.
Cross section of 2nd HEV IPM motor

2nd IPMSM has thick axial length. About 1kg of NdFeB PM is used. $625. Iron and cupper are only $200.

Torque 400Nm
Power 50kW
Outer Dia. 269mm
Axial length 154mm

High power and torque for volume.

Rare earth PMs

Stator iron

Rotor iron
Battery Technology

- Primary Battery - non-rechargeable battery
  - Cannot be recharged. Designed for a single use
- Secondary Battery – rechargeable battery
  - Lead-acid (Pb-acid)
  - Nickel-cadmium (NiCd)
  - Nickel-metal-hydride (NiMH)
  - Lithium-ion (Li-ion)
  - Lithium-polymer (Li-poly)
  - Sodium-sulfur
  - Zinc-air (Zn-Air)
- Secondary batteries are still evolving
  - Some metal-air batteries are under development, high energy density (500+Wh/kg), but low cycle life (25+)
Advantages of Li-Ion Batteries

- Lithium battery are considered the only viable solution for PHEV
- Li ion batteries offer high energy density:
  - 1.5 times NiMH; 3 times lead acid
- High power density
- Long life cycles
  - 1000 vs. 300 lead acid;
- Low memory effect; deep discharge cycles
- High cell voltage (3.2V vs. 1.2V)
- Low self discharge, long shelf life – only 5% discharge loss per month; 10% for NiMH, 20% for NiCd

model 18650, energy
3.2V*1.5Ah=4.8Wh;
  Lithium:
  228Wh/L;
  120-200Wh/kg
  Lead Acid:
  85Wh/L; 39Wh/kg
Disadvantages of Li-Ion

- Expensive -- 40% more than NiCd.
- Delicate -- battery temp must be monitored from within (which raises the price), and sealed particularly well.
- Regulations -- when shipping Li-Ion batteries in bulk (which also raises the price).
- Class 9 miscellaneous hazardous material
Environmental Impact of Li-Ion Batteries

- Rechargeable batteries are often recyclable.
- Oxidized Lithium is non-toxic, and can be extracted from the battery, neutralized, and used as feedstock for new Li-Ion batteries.
- The problem with...lithium batteries is that none of the existing electrode materials alone can deliver all the required performance characteristics including high capacity, higher operating voltage, and long cycle life. Consequently, researchers are trying to optimize available electrode materials by designing new composite structures on the nanoscale.
Issues of Lithium Batteries

- Safety
  - Electrolyte spill
  - Smoke
  - Fire
  - Explosion
- Capacity fade
  - Less miles every month
- Life cycle
  - Battery end of life earlier than expected
  - Deep discharge, charge sustain, vs. battery life
Reduced Environment Impact: CO2 Footprint of the AGV

- AGV (Automotrice Grande Vitesse) CO2 Emissions:
  - 2.2 gr CO2

Compared to other transportation modes:
- Bus: 30 gr CO2
- Minivan: 115 gr CO2
- Airplane: 153 gr CO2
Energy Optimization: Recovering Braking Energy

Traction

Electric Sub-Station

Braking Energy Feeding

Braking

Dissipation

Feeding
Traction motor is a multi-physical component (electro-mechanical) subject to severe loads and constraints.

- High torque and speed
- High voltage
- Reliability & life duration
- Thermal
- Noise
- Pollution
- Low volume & mass
- Vibrations & chocks
## TGV: a 25 years history

<table>
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<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>TGV Paris-Sud est</strong></td>
<td><strong>TGV Atlantique</strong></td>
<td><strong>Eurostar</strong></td>
<td><strong>AGV</strong> High speed EMU</td>
</tr>
<tr>
<td>Type</td>
<td>DC</td>
<td>Synchronous Wound rotor</td>
<td>Induction</td>
<td>Synchronous Rotor magnets</td>
</tr>
<tr>
<td>Equipower kW</td>
<td>535</td>
<td>1130</td>
<td>1020</td>
<td>720</td>
</tr>
<tr>
<td>Weight Kg</td>
<td>1560</td>
<td>1525</td>
<td>1260</td>
<td>720</td>
</tr>
<tr>
<td>Ratio Kg/KW</td>
<td>2,9</td>
<td>1,35</td>
<td>1,23</td>
<td>1,00</td>
</tr>
</tbody>
</table>
The AGV Train

From the TGV
an Articulated train with *Concentrated* Motorisation

to the AGV
an Articulated train with *distributed* Motorisation
Traction motors specificities

• Embedded device:
  • Severe mechanical environment
    • Low volume & mass
      • High power density
  • Pollution
    • Severe thermal environment
    • High torque at very low speed
  • Voltage & current waveforms with high harmonic level (inverters)
    • 12 to 20 h/day service
  • Guaranteed life duration: 30 or 40 years
  • Safety requirements
**PM Machines Types**

- **Surface PM** machines are dominant class of PM machines in the world today.
- **Interior PM** machines bury magnets inside the rotor, creating a salient-pole synchronous machine.
Requirements for hybrid electric vehicles

- Large torque and higher power density
- High torque at low speeds for starting and uphill climb
- High power at high cruising speeds
- Maximum efficiency over wide speed and torque ranges
- Wide speed range with constant power mode, exceeding 2-5 times the base speed
- Optimum compromise between motor peak torque and inverter volt-ampere ratings
Requirements for hybrid electric vehicles-2

- Short term overload capability, typically twice the rated torque over short duration
- Low cogging torque, low ripple and low acoustic noise
- Distributed, short- pitched and concentric stator windings.
- Optimum stator winding design with lowest THD factors
- Rotor design with magnets orientation for optimum d-q reactances for best reluctance and magnet torques
- Reduction of magnetic saturation due to cross-coupling limits to open circuit voltage and total harmonic contents
Requirements for hybrid electric vehicles

- Low stator copper and low iron losses at high speed
- High reliability for all operating conditions
- Minimum weight and smallest size
- Low fuel consumption rate (litre/km)
- New ICE engine technology with hybrid gasoline/diesel
- Homogenous charge-compression ignition (HCCI)
- Clean, ecologically benign and environmentally friendly
- Minimum vibration, quiet, smooth and comfortable ride
Requirements for hybrid electric vehicles-4

• Aesthetically acceptable to customers, aerodynamic design for lowest drag at cruising speed
• Better battery power, and self-charging
• Smart sensors and interfaces
• Least magnet flux leakage and maximum airgap fluxes
• Magnet demagnetization withstand to armature reaction
• Temperature and surface corrosion constraints of magnets
• Effects of shear stress on permeability of PM materials
• Minimum gear and more direct drive
Requirements for hybrid electric vehicles-5

- Regenerative braking and short charging cycle of batteries
- Impulse charging of batteries
- Plug-in during off peak periods of daily loading cycles
- No plug-in and hybrid transmission
- Quick plug-in charging and minimum gas generation
- PV solar panel body for self-charging of on-board battery for air conditioners and automobile smart power system.
- Seamless transfer between engine and electric traction
Requirements for hybrid electric vehicles-6

- Minimum maintenance, highest reliability and high efficiency
- Lowest Co$_2$ gas emission and minimum climate change.
- Rare-earth-free rotor design (switched reluctance motor) for niche applications considering security of supply and high price of rare earth permanent magnets, etc.
- Taxes and duties of smart vehicles at affordable prices
- Lowest initial cost and minimum operating costs.
Rotors for IM and IPM Motors

Squirrel-cage induction motor

Line-start interior permanent magnet synchronous motor
Starting Torque of Squirrel Cage Induction Motor
Developed Power and Torque in IPM Motor

\[ P_d = \frac{3V_p E_0}{X_d} \sin \delta + \frac{3V_p^2 (X_d - X_q)}{2X_d X_q} \sin 2\delta \]

\[ T_d = \frac{P}{2} \left\{ \lambda_m i_q + (L_q - L_d) i_d i_q \right\} \]
## Performance Comparisons of IPM and Induction Motors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IPM Motor</th>
<th>Induction Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor types</td>
<td>IPM</td>
<td>Induction</td>
</tr>
<tr>
<td>Input voltage: $V_i$ (V)</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>Input current: $I_i$ (A)</td>
<td>3.11</td>
<td>3.43</td>
</tr>
<tr>
<td>Input power: $W_i$ (W)</td>
<td>687</td>
<td>818</td>
</tr>
<tr>
<td>Rotor speed: $n$ (rpm) at 50 Hz</td>
<td>1500</td>
<td>1434</td>
</tr>
<tr>
<td>Torque: $T$ (Nm)</td>
<td>3.82</td>
<td>4.00</td>
</tr>
<tr>
<td>Efficiency: $\eta$ (%)</td>
<td>87.3</td>
<td>73.3</td>
</tr>
<tr>
<td>Power factor: $\text{pf}$ (%)</td>
<td>98.1</td>
<td>68.8</td>
</tr>
<tr>
<td>Output power: $P_o$ (W)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Eff. x pf product (%)</td>
<td>85.6</td>
<td>50.4</td>
</tr>
<tr>
<td>Maximum output: $P_{\text{max}}$ (W)</td>
<td>960</td>
<td>1240</td>
</tr>
</tbody>
</table>
Challenges for IPM Designs

- An IPM motor is a hybrid motor with no saliency.
- Create airgap saliency variation of d-q axis reluctances without varying physical air gap of the IPM motor.
- Varying and control of permanent magnetic (PM) excitation of rotor of IPM motor.
- Optimum variation of PM torque and reluctance torque components for specific applications.
- Availability and security of PM materials, weight, size, and overall cost of IPM motor.
- Smart ac-dc converter and dc-ac inverter for IPM traction motor drive and IPM generator for charging battery.
Hybrid IPM Patent
Rotors of Hysteresis, Reluctance, Squirrel Cage and IPM Motors
Rotors of Squirrel Cage and IPM Motors
Experimental IPM Motor (1982, MUN)
Cross Section of IPM Motor

- Stator iron lamination
- Rotor iron lamination
- Cage bar
- Permanent Magnet
- Shaft
- Conducting material

Unit: mm
Axial length 70.0
Rotor Configurations for IPM
IPM Rotor for Air Conditioners

Old

New
IPM Rotor for Compressor

IPM motor   Twin compressor
Split Window Air Conditioners
Indoor Multi-Unit Air Conditioners
Air Quality Feature

- Oxygen Enrichment Membrane
- Oxygen Supply Vacuum Pump: Sends concentrated oxygen to the indoor unit.
- Outdoor Unit: Draws in outside air.

Cross-section of module:
- Normal air
- Oxygen Enriched Air
- Oxygen Enrichment Membrane
- Frame
Annual Power Consumption Change for Air Conditioners in Japan
IPM Motor and Generator for Toyota Hybrids

IPM Generator

Gear

Front IPM Motor
2012 Toyota Prius V
Ratio of reluctance and magnet torques/total torque

- 2000 Model
  - Reluctance torque: 54%
  - Magnet torque: 46%

- 2012 Model
  - Reluctance torque: 60%
  - Magnet torque: 40%
Conclusion

- Brief introduction to the emergence of high efficiency interior permanent magnet (IPM) synchronous motors.
- A short survey of significant as well as some incremental contributions in chronological order of appearance over the past 50 years.
- Rotor design features for specific applications
- Successful simulation and experimental results
- Highlights of IPM motor drives include applications in Japanese air conditioners
Prius 2007
References
