Hybridization degree in Fuel Cell-Hybrid Systems

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Fuel Cell-Hybrid Systems (FCHS)
How hybridization works?

- For a certain load power $P_{\text{load}}(t)$, this can be supplied with some power from the fuel cell system, $P_{\text{fcs}}(t)$, being the rest of power supplied by the energy storage system, $P_{\text{ess}}(t)$. 

$$P_{\text{load}}(t) = P_{\text{fcs}}(t) + P_{\text{ess}}(t)$$
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- or from $P_{\text{fcs}}(t)$ when the load is low.
Advantages and disadvantages

- The potential advantages of a hybrid system are:
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  - Greater complexity of the control system
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- Regenerative braking energy recapture
  - The regenerative braking in automotive applications allows to improve the hydrogen economy recuperating energy from braking.
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  - The maximum power demand takes place during maximum accelerations.
  - The highest energy demands take place during long-term events (e.g., top sustained speed or grade-driving).
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• Fuel cell startup and shutdown
Some applications of FCHS

- **Fuel Cell Hybrid Vehicles**
  - The $H_2 - FCVs$ have no local contaminant emissions allowing to reduce the urban pollution.
  - The efficiency of FCS does not degrade at partial load in contrast to ICE.
  - For FCHVs, it is possibly to improve the hydrogen economy by recovering energy through regenerative braking.
  - The specific energy and the energy density of hydrogen are much larger than that of batteries: $H_2 - FCVs$ are a more competitive solution than pure-battery electric vehicles.
Some applications of FCHS

<table>
<thead>
<tr>
<th></th>
<th>Specific energy [Wh kg(^{-1})]</th>
<th>Energy density [Wh l(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (70 MPa)</td>
<td>1600</td>
<td>770</td>
</tr>
<tr>
<td>Lead-acid batteries</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>Nickel-metal-hydride batteries (Ni-MH)</td>
<td>70</td>
<td>140</td>
</tr>
<tr>
<td>Lithium-ion batteries (Li-ion)</td>
<td>120</td>
<td>150</td>
</tr>
</tbody>
</table>

• Stand-Alone Residential application
  ▶ The load has an aggressive behavior:
    ★ Sudden load switching
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  ▶ The problem of the slow dynamic response is more pronounced when the FC stack is fed with hydrogen through a reformer instead of a $H_2$-pressurized tank.
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We will concentrate our attention on FCHVs
Methodology of design

The process of hybrid system-designing, or methodology of design, can be separated in four interrelated fundamental issues once the vehicle’s requirement are established:

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- Establishment of the Energy Management Strategy
Electrical topology

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- Range of admissible voltage in the \( ESS \)
The electrical topology of the system includes the following components:

- Fuel Cell System
- Fuel Cell Converter (Boost)
- DC bus
- Voltage Inverter
- Energy Storage System
- ESS Converter (Buck/Boost)
- Auxiliar Load
- Load

The power flows are represented as follows:

- $P_{fcs}(t)$ from Fuel Cell System to DC bus
- $P_{ess}(t)$ from Energy Storage System to DC bus
- $P_{aux}(t)$ from Auxiliar Load to DC bus
- $P_{load}(t)$ from DC bus to Electric Load
ESS: Batteries vs. Supercapacitors
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**Hybridization Degree (HD)**

\[ HD = \frac{P_{ess,\, max}}{P_{fcs,\, max} + P_{ess,\, max}} \times 100 \% \]

**Power/Energy ratio (P/E)**

\[ P/E = \frac{P \,[W/kg]}{E \,[Wh/kg]} \, [W/Wh] \]
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Ragone plot

Supercapacitors for FCHV

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- High Efficiency
- Low internal resistance
- Long life time
- High cycle life
In an FCS/ESS hybrid system, the FC is the primary power source:

⇒ all the energy the vehicle needs to develop the driving cycle is generated by the FC itself.
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► Transitory driving conditions: with the assistance of ESS, the hybrid system it must have a response time to fulfill a certain acceleration (0 to 60 mph in 10 s).

• **Hydrogen economy.** The load varies strongly from very low powers to relatively high powers → the FC it is oversized most of the time. In addition, the FC efficiency is strongly degraded for low powers → the FC is working most of the time in its low efficiency zone.
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Hybridization is necessary!

The question is how to determine the most convenient hybridization degree
## Simulation results - Vehicle specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle total mass</td>
<td>$M$</td>
<td>1380</td>
<td>kg</td>
</tr>
<tr>
<td>Frontal area</td>
<td>$A_f$</td>
<td>2</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>$C_d$</td>
<td>0.335</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
<td>$f_r$</td>
<td>0.009</td>
<td>-</td>
</tr>
<tr>
<td>Air density</td>
<td>$\rho_a$</td>
<td>1.2</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>$g$</td>
<td>9.8</td>
<td>m s$^{-2}$</td>
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2) Urban Dynamometer Driving Schedule (UDDS)
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1) Histogram considering the braking energy: NEDC

Energy braking: 12.5% of traction energy
2) Histogram considering the braking energy: UDDS

Energy braking: 17.5% of traction energy
3) Histogram considering the braking energy: HWFET

Energy braking: 4.5% of traction energy

Simulation results - Histogram
Simulation results - Power demand vs. vehicle speed

Results using ADVISOR Small vehicle model

- 6.5% Grade 600kg payload
- 6.5% Grade no payload
Simulation results - Traction power requirements

<table>
<thead>
<tr>
<th>Traction power requirements</th>
<th>Power [kW]</th>
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<tbody>
<tr>
<td><strong>Sustained driving condition:</strong></td>
<td></td>
</tr>
<tr>
<td>Top speed <em>(150 kph)</em></td>
<td>44.1</td>
</tr>
<tr>
<td>88.5 kph <em>at 6.5 % grade without overweight</em></td>
<td>37.3</td>
</tr>
<tr>
<td>88.5 kph <em>at 6.5 % grade with overweight</em> <em>(600 kg)</em></td>
<td>49.9</td>
</tr>
<tr>
<td><strong>Transitory driving condition:</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration <em>(0 to 96.5 kph in 10 s)</em></td>
<td>93.1</td>
</tr>
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Conclusions

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- Thus, the FCS is often working disadvantageously, specially in NEDC and UDDS, since the efficiency is low in this range.
- The most frequent power range of power that in the driving cycles is much lower than the minimum FCS power necessary to meet the drivability requirements (49.9 kW).
Consequently, there is a conflict between drivability and efficiency.
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• It is necessary to combine the Hybridization Degree with the Energy Management Strategies.
Moltes gràcies!