Intro to parallel and series/parallel HEV architectures

Vehicle controller design review
Parallel HEV

- ICE and ED2 mechanically coupled to combine traction power
  \[
  n_{ice} T_{ice} + n_2 T_2 = nT
  \]
- Reduced size ED2; in a “micro” hybrid, ED2 is a low-power starter/alternator
- One electric drive: it is not possible to have electric drive traction and battery charging at the same time
- Requires multi-gear transmission
Series/Parallel HEV

- ICE, ED1 and ED2 mechanically coupled via a planetary gear; ICE and electric drive can combine traction power
- Capable of realizing HEV efficiency improvements
- Simple single-gear transmission
Series/parallel HEV example: 2004 Prius

Overall drive train system power rating: 82 kW (110 hp)

Energy storage

DC-DC

500 V

3-phase inverter/rectifier 2

Electric motor/generator 2

Fuel

ICE

57 kW @ 5000 rpm

n_{ice} T_{ice}

ED2

50 kW PMSM

Transmission

508 V

Boost

buck

208 V

1.3 kWh NiMH

ED1

25 kW PMSM

3-phase inverter/rectifier 1

Electric motor/generator 1

n T

n T = n T_2 + n_{ice} T_{ice} + n_1 T_1

n = n_2 = 1.4 n_{ice} - 0.4 n_1

Planetary gear (“power split device (PSD”) animation: http://eahart.com/flash/PSDAnim.swf

n T

n_1

n_2

n_v

T_v

V_{batt}

Planetary gear (radius r_v)

Wheels

Energy storage

n_{ice}

n_1

n_2

n_{ice}

Planetary gear (= ED2, n = n_2

planets = ICE, n_{ice}

sun = ED1, n_1

Overall drive train system power rating: 82 kW (110 hp)
Series/parallel HEV example: 2004 Prius

Power electronics (2 inverters and a boost DC-DC)

HEV drive train
Modes of operation: starting and low-speed

Overall drive train system power rating: 82 kW (110 hp)

Energy storage

208 V 1.3 kWh NiMH

DC-DC + V_Dc

500 V

3-phase inverter/rectifier

2

50 kW PMSM

57 kW @ 5000 rpm

n_ice T_ice

Fuel

ICE

3-phase inverter/rectifier

2

Electric motor/generator

2

ED2

Transmission

n T

Noise coupling (planetary gear)

V_Dc

v F_v

Wheels (radius r_v)

n_v T_v

ED1

25 kW PMSM

n_1 T_1

3-phase inverter/rectifier

1

Electric motor/generator

1

n_2 T_2

n_ice T_ice

ring = ED2, n = n_2

planets = ICE, n_ice

sun = ED1, n_1

Overall drive train system power rating:

82 kW (110 hp)
Modes of operation: cruising

Overall drive train system power rating: 82 kW (110 hp)

Energy storage

DC-DC

500 V

3-phase inverter/rectifier

2

57 kW @ 5000 rpm

n_{ice} T_{ice}

Fuel

ICE

Mechanical coupling (planetary gear)

Transmission

ED2

50 kW PMSM

n_{2} T_{2}

n T

ED1

25 kW PMSM

n_{1} T_{1}

Voltage

Wheels (radius r_v)

ring = ED2, n = n_{2}

planets = ICE, n_{ice}

sun = ED1, n_{1}

Fuel

V_{batt}

boost

buck

208 V 1.3 kWh NiMH

Overall drive train system power rating: 82 kW (110 hp)
Modes of operation: full acceleration

Overall drive train system power rating: 82 kW (110 hp)

Energy storage

V_{batt} = 500 V

DC-DC

Boost

208 V
1.3 kWh
NiMH

buck

V_{DC}

ED1

3-phase inverter/rectifier

n_1 T_1

25 kW PMSM

ED2

3-phase inverter/rectifier

n_2 T_2

50 kW PMSM

Fuel

ICE

n_{ice} T_{ice}

57 kW @ 5000 rpm

Transmission

Mechanical coupling (planetary gear)

Wheels
(radio r_v)

n_v T_v

v F_v

ring = ED2, n = n_2

planets = ICE, n_{ice}

sun = ED1, n_1

Overall drive train system power rating: 82 kW (110 hp)
Modes of operation: deceleration/braking

Overall drive train system power rating: 82 kW (110 hp)

Energy storage

208 V 1.3 kWh NiMH

V_{batt}

500 V DC-DC + V_{DC} -

50 kW PMSM

57 kW @ 5000 rpm

n_{ice} T_{ice}

Fuel ICE

Electric motor/generator 2

Transmission

Mechanical coupling (planetary gear)

1.3 kWh NiMH

V_{batt}

ED1

ED2

3-phase inverter/rectifier 1

n_1 T_1

n T

n_2 T_2

n_v T_v

Wheels (radius r_v)

ring = ED2, n = n_2

planets = ICE, n_{ice}

sun = ED1, n_1

Overall drive train system power rating: 82 kW (110 hp)
Summary

• HEV
  – Electrified drivetrain offers efficiency improvements
  – Battery system: relatively small energy capacity, but relatively large power rating

• PHEV or EV
  – Fuel displaced by electricity
  – Same efficiency improvements as HEV
  – Battery system: large energy capacity and large power rating
Vehicle Controller Design Review

System small-signal model:

\[ G_c(s) f_{vc}(s) G_{EV}(s) f_v(s) G_{phy}(s) \rightarrow v(s) \]

Vehicle controller

\[ G_c(s) = G_{cm} \left( 1 + \frac{\omega_z}{s} \right) \]

Goal: choose the PI controller parameters \( G_{cm} \) and \( \omega_z \) to minimize settling time \( T_{settle} \) upon a step in \( v_{ref} \), subject to an overshoot constraint

EV example:

\[
\begin{align*}
M_v &= 1500; & \text{% Vehicle curb weight + 250 kg passenger and cargo} \\
C_d &= 0.26; & \text{% Coefficient of Drag} \\
C_r &= 0.01; & \text{% Coefficient of Friction} \\
A_v &= 2.16; & \text{% Front area [m^2]} \\
\rho_{\text{air}} &= 1.204; & \text{% Air density [kg/m^3]} \\
\end{align*}
\]
\[ G_{\text{phy}}(s) = G_{\text{phy}0} \frac{1}{1 + \frac{s}{\omega_{\text{phy}}}} \]

\[ G_{\text{phy}0} = \frac{1}{\rho C_d A_v V_1} = 0.221 \ \text{(m/s)} \]

\[ f_{\text{phy}} = \frac{1}{2\pi} \frac{\rho C_d A_v V_1}{M_v} = 0.48 \ \text{mHz} \]
$G_{\text{phy}}(s) = G_{\text{phy0}} \frac{1}{1 + s/\omega_{\text{phy}}}$

$G_{\text{phy0}} = \frac{1}{\rho C_d A v V_1}$

$f_{\text{phy}} = \frac{1}{2\pi} \frac{\rho C_d A v V_1}{M_v}$

Loop gain $T(s): f_z < f_{\text{phy}}$

$G_c(s) = G_{cm} \left(1 + \frac{\omega_z}{s}\right)$

$T(s) = G_c(s)G_{\text{phy}}(s)$
Loop gain $T(s)$: $f_z = f_{phy}$

\[
G_{phy}(s) = \frac{1}{1 + \frac{s}{\omega_{phy}}} \\
G_{phy0} = \frac{1}{\rho C_d A_v V_1} \\
f_{phy} = \frac{1}{2\pi} \frac{\rho C_d A_v V_1}{M_v}
\]

\[
G_c(s) = G_{cm} \left(1 + \frac{\omega_z}{s}\right) \\
T(s) = G_c(s)G_{phy}(s)
\]

\[
T(s) = \frac{G_{cm}}{M_v} / s \\
f_c = \frac{1}{2\pi} \frac{G_{cm}}{M_v}
\]
\[
G_{\text{phy}}(s) = G_{\text{phy}0} \frac{1}{1 + \frac{s}{\omega_{\text{phy}}}}
\]

\[
G_{\text{phy}0} = \frac{1}{\rho C_d A_v V_1}
\]

\[
f_{\text{phy}} = \frac{1}{2\pi} \frac{\rho C_d A_v V_1}{M_v}
\]

Loop gain \( T(s) \): \( f_z > f_{\text{phy}} \)

\[
G_c(s) = G_{cm} \left(1 + \frac{\omega_z}{s}\right) \quad T(s) = G_c(s)G_{\text{phy}}(s)
\]

\[
T(s) \rightarrow \frac{G_{cm}}{M_v} \frac{G_{cm}}{s}
\]

\[
f_c \approx \frac{1}{2\pi} \frac{G_{cm}}{M_v}
\]
Example $G_c(s)$

$$G_c(s) = G_{cm} \left(1 + \frac{\omega_z}{s}\right) \quad G_{cm} = 1000 \frac{N}{(m/s)} \quad f_z = 0.2 \text{ Hz}$$

$$f_c \approx \frac{1}{2\pi M_v} \frac{G_{cm}}{M_v} = 0.11 \text{ Hz}$$
Loop gain $T$: magnitude and phase responses

$G_{cm} = 1000 \frac{N}{(m/s)}$

$f_z = 0.2$ Hz

$\phi_m = 40^\circ$

$f_c = 0.17$ Hz
Step $v_{ref}$ response

- **Reference Speed**
- **EV Speed**

**Speed [mph]**

- $v_{ref}$
- $T_{settle} = 7.45 \text{ s}$

**Force [N]**

- $f_v [N]$
- $f_r [N]$

**Ttractive Power [kW]**

- $p_v [kW]$

**Overshoot computed with respect to final $v_{ref} = 20 \text{ mph}$**

CU-Boulder ECEN5017, USU ECE 6930
Improved design: choose $f_z = f_{phy}$

\[
G_{phy}(s) = G_{phy0} \frac{1}{1 + \frac{s}{\omega_{phy}}} \\
G_{phy0} = \frac{1}{\rho C_d A_v V_1} = 0.221 \text{(m/s)} \div N \\
f_{phy} = \frac{1}{2\pi} \frac{\rho C_d A_v V_1}{M_v} = 0.48 \text{ mHz}
\]

\[
G_c(s) = G_{cm} \left(1 + \frac{\omega_z}{s}\right) \\
G_{cm} = 1000 \frac{N}{(\text{m/s})} \\
f_z = f_{phy} = 0.48 \text{ mHz} \\
T(s) = \frac{G_{cm}}{M_v} \\
f_c = \frac{1}{2\pi M_v} \frac{G_{cm}}{s} = 0.11 \text{ Hz} \\
M_v = 1500 \text{ kg}
\]
Loop gain $T(s)$

Bode Diagram

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Magnitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>-50</td>
</tr>
<tr>
<td>$10^{0}$</td>
<td>-90</td>
</tr>
</tbody>
</table>

$\phi_m = 90^\circ$

$fc = 0.11$ Hz
Step $v_{ref}$ response

$T_{\text{settle}} = 5.54 \text{ s}$

$p = 0 \%$

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Improved design: choose $f_z = f_{phy}$, increase $f_c$ by increasing $G_{cm}$

$$G_c(s) = G_{cm} \left( 1 + \frac{\omega_z}{s} \right)$$

$$f_z = f_{phy} = 0.48 \text{ mHz}$$

$$G_{cm} = 10000 \frac{N}{(\text{m/s})}$$

$$T(s) = \frac{G_{cm}/M_v}{s}$$

$$f_c = \frac{1}{2\pi} \frac{G_{cm}}{M_v} = 1.1 \text{ Hz}$$
Loop gain $T(s)$
Step $v_{ref}$ response

$T_{settle} = 0.55 \text{ s}$

$p = 0.01 \%$

Reference Speed

EV Speed

Drive Force

Resistive Force

Tractive Power [kW]

Speed [mph]

Force [N]

Tractive Power [kW]

time [sec]
Improved design: choose $f_z = f_{phy}$, increase $f_c$ by increasing $G_{cm}$ further

$$G_c(s) = G_{cm}\left(1 + \frac{\omega_z}{s}\right)$$

$$f_z = f_{phy} = 0.48 \text{ mHz}$$

$$G_{cm} = 100000 \frac{N}{(m/s)}$$

$$T(s) = \frac{G_{cm}/M_v}{s}$$

$$f_c = \frac{1}{2\pi} \frac{G_{cm}}{M_v} = 11 \text{ Hz}$$
Step $v_{ref}$ response

$p = 0.2\%$

$T_{settle} = 0.47 \text{s}$

Reference Speed

EV Speed

Driving Force

Resistive Force

Tractive Power [kW]

Speed [mph]

Force [N]

Tractive Power [kW]
What is the effect of increasing $f_z$?

$$G_c(s) = G_{cm}\left(1 + \frac{\omega_z}{s}\right)$$

$$f_z = 100 f_{phy} = 0.048 \text{ Hz}$$

$$G_{cm} = 10000 \frac{N}{(m/s)}$$

$$T(s) \rightarrow \frac{G_{cm}/M_v}{s}$$

$$f_c \approx \frac{1}{2\pi \frac{G_{cm}}{M_v}} = 1.1 \text{ Hz} \quad \phi_m = 87.4^\circ$$
Step $v_{ref}$ response

$T_{settle} = 0.50 \text{ s}$

$p = 1.82 \%$

Reference Speed

EV Speed

Drive Force

Resistive Force

Tractive Power [kW]

time [sec]
Driver is given PI dynamics to control vehicle speed to a given reference. Output control value is the force command given to the vehicle drive system via gas/break pedals.
Preventing integrator wind-up

Stop integration if required gas pedal exceeds maximum available

Driver is given PI dynamics to control vehicle speed to a given reference.
Output control value is the force command given to the vehicle drive system via gas/break pedals
Step $v_{ref}$ response

- Reference Speed
- EV Speed

$t_{settle} = 0.55 \text{ s}$

$p = 0.2 \%$

- Drive Force
- Resistive Force

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Response to change in grade of road

System small-signal model:

\[ v_{ref}(s) \rightarrow G_c(s) \rightarrow f_{vc}(s) \rightarrow G_{EV}(s) \rightarrow f_v(s) \rightarrow G_{phy}(s) \rightarrow v(s) \]

Vehicle controller