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Towards a generic control-oriented model for HEV predictive energy management

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Abstract: The increased interest in model-based control techniques for the energy management of hybrid electric vehicles has led to a focus on generic modeling in order to allow an effective integration in model-based design procedures. An architecture-free model ensures modularity with a view to control design. Under mild assumptions, a generic model for the torque and the rotational speed of a hybrid electric vehicle is proposed in this article. In addition, the mathematical formulation of the fuel consumption minimization and the intrinsic problem of torque split are addressed. In order to illustrate its ability to handle the constraints, a model predictive control formulation is presented and applied to a dual-clutch transmission hybrid architecture.

Keywords: hybrid electric vehicle, generic model, energy management, MPC

1. INTRODUCTION

In recent years, stringent CO₂ emission regulations, as well as the depletion of fossil fuel resources have triggered a determined orientation toward alternative transportation technologies, such as hybrid electric vehicles (HEV).

For HEV, one of the most challenging problems concerning fuel consumption optimization is computation of the torque split between the engine and the motor. In the literature several techniques have been proposed: dynamic programming, which provides the global optimum, under the assumption of perfect information (Sundstrom et al., 2008), rule-based (Goerke et al., 2015), ECMS - Equivalent Consumption Minimization Strategy (Sciaretta et al., 2004) and its variations: A-ECMS (Musardo et al., 2005), T-ECMS (Sciaretta et al., 2004); fuzzy, genetic algorithms, game theory, deterministic Model Predictive Control (MPC) (Cairano et al., 2011), (Borhan et al., 2012), (Lu et al., 2013) and stochastic MPC (Ripaccioli et al., 2010), (Josevski and Abel, 2014). The ability to cope with constraints and also the possibility nowadays to collect information about the future speed and road profile have made the latter a very attractive method.

Model-based methods have drawn attention due to the inherent robustness of the solution, but they depend on the powertrain architecture, i.e. electric machine position and transmission type. In Rizzoni et al. (1999) a generalized model for HEV components and energy flow was proposed and in Chen et al. (2009) a global model for different vehicle types (conventional, hybrid, electric) was described, but the functional modes for each configuration were not detailed. The torque values at different levels (wheel, gearbox, crankshaft) and rotational speed of components are mandatory for a supervisory control and in the absence of a comprehensive parameterization, the control would have to be adapted for each particular configuration. In this paper, a generic control-oriented model is proposed, that will complete the HEV architecture description and will also make a contribution from a control point of view.

The improvements in fuel consumption by the use of telemetry data have been the object of several publications, such as (Kim et al., 2008) or (Manzie et al., 2012). In the former, a maximum headway of 400 m was tested, whereas in the latter the prediction was specified on a time headway, with optimal values found to be on the order of 30 s. However, within the use of the MPC method, smaller prediction horizon values are used, mostly below 20 s.

In this paper, the velocity profile and the gear engaged are assumed known in advance for a given time horizon and therefore, only the torque split problem will be addressed. For a charge sustaining operation, a state-of-charge (SOC) balance condition is usually imposed; appropriate penalty factors can solve this problem, but they depend on the driving cycle characteristics. MPC final state constraints can lead to conservative results for short prediction horizons, as SOC varies in a small range. In this respect, the present paper proposes a new approach, that uses distance-varying limits for SOC, enforcing the convergence to the initial value, as the vehicle reaches its destination.

The article is organized as follows: first, a generic model with the associated assumptions, equations and configurations will be presented and validated on a case-study architecture. In the second part, the MPC - based energy
management problem will be formulated; the simulation results obtained and the conclusions complete the paper.

NOTATIONS

- ICE - internal combustion engine
- EM - electric machine
- DCT - dual-clutch transmission
- $R_i$ - gear ratio engaged on $i$th shaft (includes neutral definition), $i \in \{1 : \text{odd}, 2 : \text{even}\}$
- $C_i$ - clutch status (0 - open, 1 - closed)
- $N_i = \min(R_i, 1)$ - used to define the case where one of the shafts is decoupled
- $F_{DR_i}$ - axle ratio corresponding to $i$th shaft
- crk, prim, sec, w - crankshaft, primary, secondary and wheel, respectively
- $rat_{pos}^{EM}$ - ratio between the EM and the corresponding shaft where it is connected ($pos$ - position)
- $rat_{IIC}^{pos}$ - ratio between the ICE torque at $pos$ level and the ICE torque at crankshaft
- $rat_{w/pos}^{EM}$ - ratio from the EM placed at $pos$ to the wheel
- $\omega_{ctrl}^{ICE}$ - engine speed for a series architecture; for the others: idle speed or 0 rpm, in case of engine stop
- $R_w$ - wheel radius

2. GENERIC HEV CONTROL-ORIENTED MODEL

The proposed model aims to cover a large class of HEV architectures under the following assumptions:

(i) potential EM connected to the crankshaft, primary shaft, secondary shaft and to the wheel, as in Fig. 1
(ii) one battery
(iii) one gear-shaft EM (an EM to the either odd or even shaft, but not both - for a dual-clutch transmission). The notation conventions assign the shaft index $2$ to the EM connected to the primary. If the EM is connected to the odd shaft, the indexes will be switched.
(iv) gear and clutch dynamic not considered
(v) gear efficiency dependent only on rotational speed

First, a parallel architecture will be considered and subsequently it will be shown that the model can be employed for other architectures. Recall also that in Chapter 4 of Guzzella and Sciarretta (2007) the power-split case was treated and a very compact model was proposed in the form:

$$
\begin{bmatrix}
T_f \\
T_g
\end{bmatrix} = M \begin{bmatrix}
T_{ic} \\
T_{in}
\end{bmatrix}, \begin{bmatrix}
\omega_{ic} \\
\omega_{mot}
\end{bmatrix} = M \begin{bmatrix}
\omega_f \\
\omega_g
\end{bmatrix},
$$

(1)

2.2 Torque and rotational speed expressions

From an energy management point of view, the torque expression at the wheel level includes the complete information about a HEV architecture (EM position and gearbox). For a detailed characterization, the equations below describe the relationship between the components torque and the torque delivered at the 4 shafts (crk, prim, sec, w) and also the rotational speeds, as functions of the vehicle speed ($v$) and $\omega_{IIE}$. Table 1 gives a description of these configurations, with EM connected to pos $\subseteq \{crk, prim, sec, w\}$. This implies that for pos $\notin pos$, $rat_{EM}^{pos} = 0$. 

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1 = 0, C_2 \in {0, 1}$</td>
</tr>
<tr>
<td>2</td>
<td>$C_1, C_2 \in {0, 1}, prim \in pos$</td>
</tr>
<tr>
<td>3</td>
<td>$C_1 = 0, C_2 = 1$</td>
</tr>
</tbody>
</table>

Table 1. Architectures description, EM connected to pos
\[ T_w = r_{ICE}^T T_{ICE} + \sum_{pos} w_{pos} T_{EM} \]

with \( \text{pos} \in \{\text{crk}, \text{prim}, \text{sec}, w\} \)

\[ \begin{bmatrix} T_{crk} \cr T_{prim} \cr T_{sec} \cr T_w \end{bmatrix} = A T \begin{bmatrix} T_{ICE} \\ T_{crk}^T \cr T_{prim}^T \\ T_{sec}^T \\ T_{EM}^T \cr T_{EM} \end{bmatrix} + \begin{bmatrix} w_{ICE} \\ w_{crk} \\ w_{prim} \\ w_{sec} \\ w_{EM} \end{bmatrix} = A_w \begin{bmatrix} v \\ \omega_{ICE} \end{bmatrix} \]

(3)

\[ A_T = \begin{bmatrix} 1 & r_{ICE}^T & 0 & 0 & 0 \\ r_{crk}^T & r_{crk}^T & r_{crk}^T & r_{crk}^T & r_{crk}^T \\ r_{sec}^T & r_{sec}^T & r_{sec}^T & r_{sec}^T & r_{sec}^T \\ r_{EM}^T & r_{EM}^T & r_{EM}^T & r_{EM}^T & r_{EM}^T \\ r_w & r_w & r_w & r_w & 0 \end{bmatrix} \]

\[ A_w = \begin{bmatrix} r_{prim} \cr r_{sec}^T \cr r_{EM}^T \cr r_w \cr 0 \end{bmatrix} \]

(5)

\[ r_{prim} = (1 - C_1 - N_2 C_2) \]

\[ r_{sec} = R_1 C_1 + R_2 C_2 \]

\[ r_{EM} = F(D_{R1} R_1 C_1 + F(D_{R2} R_2 C_2) \]

\[ r_w = \sum_{pos} w_{pos} T_{pos} \]

\[ \text{S} = \frac{-OCV (SOC) - \sqrt{OCV (SOC)^2 - 4R (SOC) P_b}}{2R (SOC) Q_{max}} \]

where, for \( \text{pos} \in \{\text{crk}, \text{prim}, \text{sec}, w\} \) the battery power is:

\[ P_b = \sum_{pos} \frac{\pi}{30} w_{pos} T_{pos} \]

Note that the proposed model can also describe the series architecture. In this case, the engine is decoupled from the drivetrain and there are two EM: one for traction, and another that acts as a generator, to convert the engine mechanical output into electricity. From Fig. 1 this implies:

\[ C_1 = 0, C_2 = 0, \]

and the terms in matrices \( A_T \) and \( A_w \) combine products between the 2 clutches in order to appropriately integrate special use-cases of a DCT, as detailed in Table 3. For instance, (6) defines the ratio between the torque at primary and at crankshaft and it is the arithmetical expression for the logical OR operation. Equation (10) is detailed in Table 2, which is well defined for \( r_{EM} \neq 0 \). For a DCT, if both clutches are closed, the EM will run at the same speed as the ICE, the operating point being defined by the vehicle speed and the gear engaged on the odd shaft (\( R_1 \)).

\[ \text{Table 2. EM to primary shaft, (10) description} \]

<table>
<thead>
<tr>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( r_{EM} )</th>
<th>( r_{EM} )</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( R_2 ) 1, 2</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>( R_2 ) 1, 2, 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>( R_2 ) 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>( R_1 ) 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The condition that ensures the engine is disconnected from the drive (its speed being therefore defined by \( \omega_{ICE}^{ctrl} \)) is \( C_1 = N_2 = 0 \). This covers the cases where both clutches are open and also the charge at standstill mode \( (C_1 = 0, C_2 = 1) \). The latter is defined for an architecture with one EM to the primary shaft and involves decoupling the engine from the wheel \( (N_1 = 0) \) and closing the clutch between the engine and the \( EM^{prim} \) \( (C_2 = 1)\).

\[ \text{In the case of a DCT, } C_1 \text{ will be set to zero, according to assumption (iii) from section 2. Thus, the EM rotational speed will be equal to } \omega_{ICE}^{ctrl} \text{ and this is defined in the } \omega_{EM}^{prim} \text{ expression by the term } C_2 (1 - C_1) (1 - N_2). \]

2.3 Case-study: hybrid architecture with a DCT

In this section, a DCT hybrid architecture is considered, with one EM connected to the primary shaft. This configuration allows both clutches to be simultaneously closed in same particular cases: take-off and charge during driving, in parallel mode (the ICE and EM run at the same speed). In this case, the even shaft must be decoupled from the wheel (\( R_2 = 0 \)). The Table 3 summarizes the use-cases with respect to clutch states and even shaft (coupled/decoupled).

\[ \text{Table 3. Hybrid DCT functional modes} \]

<table>
<thead>
<tr>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( N_2 )</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>standstill, sailing</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>electric driving, regenerative braking</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>hybrid or conventional, even gear engaged</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>charge during standstill</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>conventional driving, odd gear engaged</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>hybrid driving</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>take-off, charge during driving (parallel mode)</td>
</tr>
</tbody>
</table>

The charge during driving case can appear under 2 forms: torque split and parallel mode, as presented in Fig. 4. In
Square Error associated to validation data are summarized for a SI and CI engine, respectively, and also in Table 4, where the RMSE (Root Mean Square Error) whose accuracy is quantified in the last column of (16c):

\[ m_f = \left( a_1^2 \omega_{ICE}^2 + a_1 \omega_{ICE} + a_0 \right) T_{ICE} \]

\[ + b_1^2 \omega_{ICE}^2 + b_1 \omega_{ICE} + b_0 \]

where \[ p_j = a_j T_{ICE} + b_j, j = 0 \ldots 2 \]

\[ T_{ICE}^\text{min}(i) \leq T_{ICE} \leq T_{ICE}^\text{max}(i), i = 1 \ldots N_{\text{part}} \]

The optimization criterion was chosen such that its expression includes the trade-off between the use of the 2 power sources, similar to ECMS. Due to convexity requirements and considering the expression for the fuel consumption approximation a weighted sum of the square of the two powers was used:

\[ \min_{i} \sum_{i=k}^{k+N-1} P_f^2(i) + \lambda P_d^2(i) \]  

(18)

and by detailing the terms, it can be expressed as:

\[ \min_{i} \sum_{i=k}^{k+N-1} m_f^2(i) + \lambda \left( \frac{1}{H_L} Q_{\text{max}} \text{OCV}(k) S\text{SOC}(i)^2 \right) \]  

(19)

where \[ k \] is the current step, \( N \) is the prediction horizon, \( H_L \) is the lower heating value of the fuel and SOC variation is given by (13). Another quadratic criterion is currently under study, where the electrical consumption is expressed by the difference between the electrochemical power and its minimal value, defined by constraints. This new criterion takes into account cases where \( P_e \) is negative.

For a charge-sustaining operation mode, a particular attention must be paid to the SOC balance. This could be ensured by choosing appropriate values for the penalty factor \( \lambda \), but it is cycle-dependent (which is in turn characterized by speed profile and total duration). In this paper, distance-varying min-max limits for SOC were used:

\[ SOC_{\text{min}}(k) = SOC_0 - (SOC_0 - SOC_{\text{min}}) e^{-\frac{k-1}{\text{dist}\text{Tot}}} \]

\[ SOC_{\text{max}}(k) = SOC_0 + (SOC_{\text{max}} - SOC_0) e^{-\frac{k-1}{\text{dist}\text{Tot}}} \]  

(20)
where $v$ represents the vector of future commands: 

$$
\begin{align*}
\mathbf{v}_k &= \sum_{i=1}^{N} \mathbf{v}_i \\
\mathbf{u}_k &= \sum_{i=1}^{N} \mathbf{u}_i \\
\end{align*}
$$

The idea is to constrain SOC to gradually approach its initial value as the ratio between the actual distance and the total distance increases and, at the same time, allowing it a wide range of variation in the first part of the trajectory ($SOC_{\text{min}}, SOC_{\text{max}}$ represent the physical limitations of the battery which were set at 20% and 90%, respectively). A final SOC equal to the initial value could be chosen with respect to history data.

### 3.1 MPC formulation

The model-based predictive control strategy involves the resolution of a finite-time horizon optimization problem, at each time instant $k$:

$$
\min_{U} \sum_{i=1}^{N} \left( \Delta x_{k+i}^T Q \Delta x_{k+i} + \Delta u_{k+i-1}^T R \Delta u_{k+i-1} \right) \quad \text{s.t.} \quad \begin{cases} 
\Delta x_{k+i} = A_k \Delta x_k + B_k \mathbf{u}_k + D_k, \\
\mathbf{u}_{k+i-1} = \mathbf{u}_{k+i} + \Delta \mathbf{u}_{k+i}, \\
\mathbf{u}_{\text{min}} \leq \mathbf{u}_{k+i-1} \leq \mathbf{u}_{\text{max}}, \quad i = 1, ..., N \\
\mathbf{x}_{\text{min}} \leq \mathbf{x}_{k+i} \leq \mathbf{x}_{\text{max}}, \quad i = 1, ..., N 
\end{cases}
$$

The problem is reformulated as a quadratic programming, where $U$ represents the vector of future commands:

$$
\begin{align*}
\min_{U} \; & \frac{1}{2} U^T H U + F^T U \\
\text{s.t.} \; & \begin{cases} 
A_{ineq} U \leq b_{ineq} \\
A_{eq} U = b_{eq}
\end{cases}
\end{align*}
$$

In our case, the only state variable is SOC whose model (13) is nonlinear; in Caurano et al. (2011), Feng et al. (2015) a simplified linear model was used, but for a NiMh battery, whose operating range was restricted to a narrow interval: 40%-60%. However, outside this range, the model is no longer valid. Here, a linearization at the operating point is performed, under the assumption that open circuit voltage and internal resistance are constant during the prediction. A Linear Time Varying (LTV) system is obtained:

$$
x_{k+1} = A_k x_k + B_k u_k + D_k
$$

where $x = SOC, A_k = 1, u_k = T_{ICE}(k)$ and $D_k$ is a residual term due to linearization. It can be noticed that $A_k$ is constant, which reflects the integral behavior of SOC. The model complexity is given by the time-variance of $B_k$ and $D_k$, which depend on EM rotational speed and torque demand. After linear algebra manipulations, we have:

$$
\begin{align*}
X_k &= \Phi_k x_k + \Psi_k u_k + V_k \\
\Phi_k(i) &= \text{ones}(N, 1), \Psi_k(i,j) = \begin{bmatrix} B_{k+j-1} & j \leq i \\
0 & \text{else}
\end{bmatrix} \\
V_k^T &= \begin{bmatrix} D_k & D_k & D_{k+1} & \cdots & \sum_{i=1}^{N} D_{k+i-1} \end{bmatrix}
\end{align*}
$$

where $x$ is the SOC value at instant $k$ and $X_k, U_k$ the vectors of future states and commands, respectively.

As in (19), $\Delta SOC$ has to appear in an explicit form:

$$
\Delta X_k = D_k (\Phi_k x_k + \Psi_k U_k + V_k) + X_{k0}
$$

$$
X_{k0} = \begin{bmatrix} x_k \\
0 \\
\vdots
\end{bmatrix} \\
D_k (i,j) = \begin{bmatrix} -1 & i = j \\
1 & i = j + 1 \\
0 & \text{else}
\end{bmatrix}
$$

From (17), we have:

$$
n_i = o(\omega_{ICE}) T_{ICE} + \beta(\omega_{ICE})
$$

Therefore, the optimization criterion (18) is reduced to a quadratic formulation as in (22), where the positivity requirement is always verified:

$$
H = \Psi_k^T D_k^T Q D_k \Psi_k + \bar{\alpha}^2
$$

$$
F = \Psi_k^T D_k^T Q (D_k (\Phi_k x_k + V_k) + X_{k0}) + \bar{\alpha} \bar{\beta}
$$

with $\bar{\alpha} = \text{diag}(\alpha(\omega_{ICE,k+i-1}))$, $\bar{\beta}(i) = \beta(\omega_{ICE,k+i-1})$ and $Q = \text{diag}\left(\frac{1}{h C_{\text{eq}} Q_{max} OCV}^2\right)$. Future vehicle reference speed and gear engaged are considered known for the next $N$ s and therefore, from (3) and (5) we can determine the rotational speeds for ICE and EM:

$$
\omega_{ICE} = \frac{R_w}{R_{\text{w}}} \frac{v}{1 - C_1 - N_2 C_2} \omega_{\text{cri}}^{\text{ICE}}
$$

$$
\omega_{EM} = \frac{R_{\text{EM}}}{R_{\text{w}}} \frac{v}{1 + N_2 C_2} \omega_{\text{cri}}^{\text{ICE}}
$$

The rotational speeds establish the torque and power constraints for each prediction step that can be easily
expressed from (2), whereas SOC constraints (20) are imposed from (24a):

\[ T_{ICE} = \frac{T_w - r_{EM}^w T_{EM}}{r_{ICE}} \]  
(29a)

\[ T_{ICE}^{min}(\omega_{ICE}) \leq T_{ICE} \leq T_{ICE}^{max}(\omega_{ICE}) \]  
(29b)

\[ T_{EM}^{min}(\omega_{EM}) \leq T_{EM} \leq T_{EM}^{max}(\omega_{EM}) \]  
(29c)

\[ P_{EM}^{min}(\omega_{EM}) \leq \frac{\pi}{30} \omega_{EM} T_{EM} \leq P_{EM}^{max}(\omega_{EM}) \]  
(29d)

\[ SOC_{min}^{(k)} - \epsilon_k \leq X_k \leq SOC_{max}^{(k)} + \epsilon_k \]  
(29e)

where the superscript \textit{prim} was neglected, due to the presence of a single EM and \( \epsilon_k \) are slack variables. All the studied driving cycles have power requirements achievable with the conventional mode (ICE only), so torque and power limitations can be imposed as hard constraints, without affecting the recursive feasibility of the receding horizon optimization. On the contrary, in the case of distance-varying SOC limitations, infeasibility might occur, especially toward the reset distance, where there is a narrow range of variation. These limitations are therefore included as soft constraints.

3.2 Simulation and results

The control law was tested under Matlab/Simulink and the behavior of the vehicle was simulated by a high-fidelity model, designed in AMESim. The total distance was considered known \textit{a priori} and a prediction horizon \( N = 5s \) was used. The results are summarized in Table 6, where the comparison is made with the consumption in conventional mode; in the case of a final SOC value different from the initial one, a consumption correction was performed. For all the scenarios the control parameters are the same. It can be seen that the hybrid vehicle with a MPC strategy offers a consumption gain up to 26%.

Table 6. Fuel consumption [L/100 km] for different drive cycles; ICE-only without stop & start vs MPC for HEV

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Conventional</th>
<th>Hybrid</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTEMIS road</td>
<td>5.8</td>
<td>5.32</td>
<td>8.2%</td>
</tr>
<tr>
<td>ARTEMIS urban</td>
<td>9.38</td>
<td>6.9</td>
<td>26.4%</td>
</tr>
<tr>
<td>ARTEMIS highway</td>
<td>8.2</td>
<td>8.01</td>
<td>2.3%</td>
</tr>
<tr>
<td>FTP-75</td>
<td>6.22</td>
<td>5.28</td>
<td>15.1%</td>
</tr>
<tr>
<td>NEDC</td>
<td>5.76</td>
<td>5.01</td>
<td>13%</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS AND OUTLOOK

A generic parameterization under certain assumptions has been proposed for a hybrid powertrain, with detailed expressions for series and parallel architectures. For the energy management part, an MPC - based strategy has been presented and validated in simulation (Matlab and AMESim) on a hybrid DCT case study. Current simulations show that encouraging results can be obtained with a MPC strategy. The quadratic formulation is still under investigation. In addition, a sensitivity analysis with respect to driver behavior and to tuning parameters (prediction horizon, penalty factor, reset distance), as well as a stability analysis will be the object of a future study.

REFERENCES


