
Efficient management of vehicular energy system and its control

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Abstract: This paper deals with energy management in Hybrid Electric vehicles. It proposes a method for model reduction. Efficient energy management and reduction in fuel consumption is achieved using optimization techniques and also using lightweight materials. Modification of optimizing algorithms is also proposed. Novelty and advantages of proposed method proved by encouraging simulation results. An attempt has been made for finding the optimal solution to popularize the technique.

Keywords: Hybrid Electric vehicles, Energy management, Fuel economy, Composite materials.

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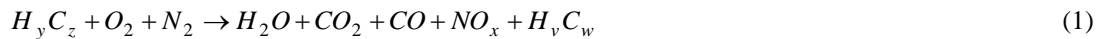
1 Introduction

Hybrid Electric Vehicles (HEV) vehicles require an energy management strategy to control the power split between the engine and the electric motors. Energy management can also be applied to the electric power system of a vehicle with a conventional drive train. The idea of controlling the vehicle power is initiated by the fact that energy losses in the internal combustion engine, alternator, and battery change according to their operating point. Minimizing these energy losses will result in an energy management strategy achieving higher fuel economy. Strategies that are based on heuristics can easily be implemented in a real vehicle by using a rule-based strategy [1] or by using fuzzy logic [2]. Although these strategies can offer a significant improvement in energy efficiency, they do not guarantee an optimal result in all situations. Hence, there is a requirement to develop strategies based on optimization techniques. To find the optimal solution, techniques as linear programming [3], optimal control [4], and especially Dynamic

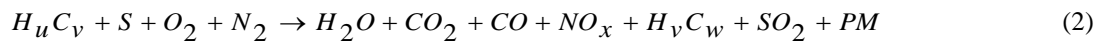
Programming [5, 6] have been studied. In general, these techniques do not offer an online solution, because they assume that the future driving cycle is entirely known. Nevertheless, their result can be used as a bench-mark for the performance of other strategies, or to derive rules for a rule-based strategy. If only the present state of the vehicle is considered, optimization at each time instant can be beneficial, but profits will be limited [7]. A different approach is taken by Kolmanovsky et.al [8] and Lin et.al in [9]. Instead of focusing on one particular driving cycle, a certain set of driving cycles is considered, resulting in a stochastic optimization approach. The difficulty is to cover a real-world driving situation with a set of individual driving cycles. The present investigation is an attempt to develop a novel method consisting of three steps. These steps are (1) Reduction of the model of the vehicle, (2) Energy management using modified dynamic programming (MDP) and (3) Use of better materials e.g. lighter materials for weight reduction.

2 Model reduction

Balenovic in [10] has proposed the following for the chemical reaction for gasoline



Diesel also contains sulfur (S) and produces considerable amounts of particle matter (PM), leading to the following reaction equation:



The relation between the mechanical power and the fuel rate for each engine speed (the fuel map):

$$\dot{m} = f(P_m, \omega) \approx f_0(\omega) + \frac{k_f}{h_f} P_m \quad (3)$$

Approximations give rise to:

$$\dot{m} = \frac{k_f}{h_f} (P_m - P_{m \min}(\omega)) \quad (4)$$

A lead-acid battery has a complex nonlinear electro-chemical behavior. Actual and approximated models proposed are given in figure 1.

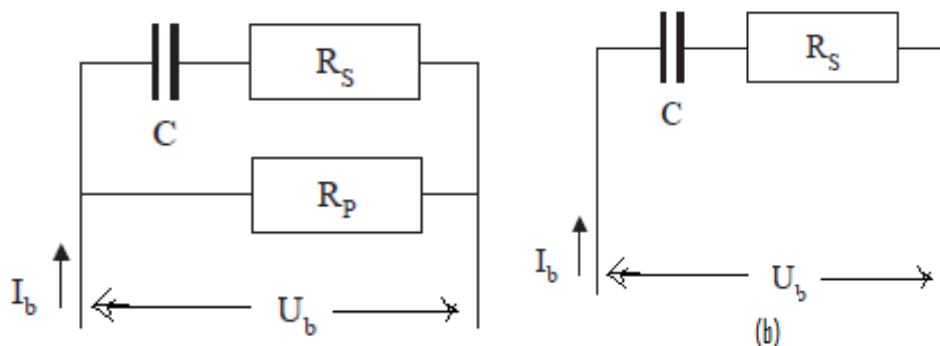


Figure 1: Circuit model of battery and approximated model

The energy level of the battery can be given by a simple integrator:

$$E_s(t) = E_s(0) + \int_0^t P_s(\tau) d\tau \quad (5)$$

The state of energy (SOE) representing the relative energy level in the battery is given by:

$$SOE = \frac{E_s}{E_{s \max}} \cdot 100\% \quad (6)$$

The battery losses in the control model is incorporated in the battery characteristic (modeled as a power based model)

$$P_b = P_s + P_{\text{loss}}(P_s, E_s, T) \quad (7)$$

Assuming that the variation in energy level and temperature is small, (7) reduces to:

$$P_b = P_s + P_{\text{loss}}(P_s) \quad (8)$$

The battery losses are approximated as quadratic with the stored power, such that (8) reduces to:

$$P_b = P_s + bP_s^2 \quad (9)$$

3 Energy management

The energy management problem is formulated as an optimization problem. Then, the problem optimized using Dynamic Programming (DP). The problem is implemented for Quadratic Programming (QP) to further reduce the computation time. Modifications are proposed for further approximation of QP. Further, problem is optimized with a form of Modified DP to further reduce computation time.

3.1. Optimization problem

The vehicle is represented by a dynamic system: $x(k+1) = f(x(k), u(k), k)$ Which has to be controlled,

such that the cost criterion: $\sum_0^n \gamma(x(k), u(k), k) \Delta t$ is minimized, satisfying the constraints:

$$\phi(x(k), u(k), k) \leq 0 \quad \psi(x(k), u(k), k) = 0$$

3.2. Dynamic Programming

Dynamic Programming (DP), [5, 6] is a method to solve a discrete time dynamic optimization problem, i.e., to find optimal sequence of control variables:

$$[u(0), \dots, u(n-1)] \quad (10)$$

That brings a system given by:

$$x(k+1) = f(x(k), u(k), k) \quad (11)$$

From state $x(0) = x_0$, while minimizing the cost function:

$$J = \sum_0^n \gamma(x(k), u(k), k) \Delta t \quad (12)$$

Four basic equations those affect the fuel consumption are given by:

$$\dot{m} = f(P_m, \omega); P_g = g(P_e, \omega); P_b = P_s + P_{loss}(P_s); E_s(k+1) = E_s(k) + P_s(k)\Delta t$$

And bounds are:

$$E_{s\min} - E_s(0) \leq \sum_{i=0}^k P_s(i)\Delta t \leq E_{s\max} - E_s(0); P_{s\min} \leq P_s \leq P_{s\max}$$

3.3. Quadratic Programming

Although the computation time of the DP routine has been reduced significantly, it is still very time consuming for long driving cycles, so for real-time implementation other modifications need to be considered.

Simplifications are introduced to achieve a Quadratic Programming structure (QP) [11], which has the advantage that a global minimum is guaranteed and short computation times can be achieved, provided that the problem is convex.

A QP problem is given by a quadratic cost criterion subject to linear constraints:

$$\min_z J(z) = \frac{1}{2} z^T H z + h^T z + h_0, \text{ subject to } A z \leq b.$$

Model approximation:

$$\text{Efficient management of vehicular energy system and its control} \quad k)$$

Cost function:

$$J = \sum_{k=0}^n \gamma(P_s(k))\Delta t$$

The decision variables are:

$$z = [P_s(1) \cdots P_s(n)]^T$$

Constraints

$$E_s(k) = E_s(0) + \sum_{i=1}^k P_s(i)\Delta t \text{ and } E_s(n) = E_s(0) \Rightarrow \sum_{i=1}^n P_s(k) = 0$$

3.4. Reduction of the QP problem

If only the cost function and the equality constraint are considered, the QP problem can be solved analytically by introducing the Lagrange function:

$$L(z, \lambda) = \sum_{k=1}^n \left\{ \varphi_2(k) P_s(k)^2 + \varphi_1(k) P_s(k) + \varphi_0(k) \right\} - \lambda \sum_{k=1}^n P_k(k)$$

Solution is

$$P_s^0(k) = \frac{\lambda - \varphi_1(k)}{2\varphi_2(k)}$$

Finally, the solution is:

$$\left. \frac{\partial \gamma(P_s)}{\partial P_s} \right|_{P_s^0} = 2\varphi_2(k) \frac{\lambda - \varphi_1(k)}{2\varphi_2(k)} + \varphi_1(k) = \lambda$$

3.5. Reduction of DP problem

When a prediction of the complete cycle is not available, an estimate of λ can be used. However, if this value is too low, E_s will increase on the long run, whereas it will decrease if the estimate is chosen too low.

Long term drift of E_s can be prevented by adapting λ online, based on the measured E_s . This can for instance be done using the following PI-type controller:

$$\lambda(k+1) = \lambda_0 + K_p(E_s(0) - E_s(k)) + K_I \sum_{i=1}^k (E_s(0) - E_s(i))\Delta t$$

As an alternative to the PI-controller, it is also possible to use MPC with zone control, which means that λ is only adapted if E_s exceeds some boundary [13].

For given λ , computing $P_s^0(k)$ using above equation is equivalent to solving at each time instant k :

$$P_s^0(k) = \arg \min_{P_s(k)} \{ \varphi_2(k)P_s(k)^2 + \varphi_1(k)P_s(k) + \varphi_0(k) - \lambda(k)P_s(k) \}$$

Instead of the quadratic approximation, if the original nonlinear cost function is used, it takes the form

$$P_s^0(k) = \arg \min_{P_s(k)} \{ \gamma(P_s(k), k) - \lambda(k)P_s(k) \}$$

This can be solved using DP with a horizon length of 1 on a dense grid.

4. Replacement of Conventional materials by Composites

In order to reduce the weight of vehicle, possible composites that can replace conventional materials are carbon fiber composites, particulate reinforced metal matrix composites and polymer composites. Basic objective is to increase the specific strength and thermal conductivity. By making vehicles smaller, lighter, and more aerodynamic, the power necessary to propel the vehicle can be reduced, and thereby also the fuel consumption. Weight reduction can be achieved by replacement of conventional materials by composites. For example, in Ford Mondeo, it is shown to that it can be made lighter by 46% [14].

5. Results and discussion

5.1 Simulation Setting and Parameters

Parameters chosen for performance measurement are: Fuel Consumption, Battery storage power and Battery state of energy. Simulations are done for the Ford Mondeo, equipped with the 42 V power net and for the New European Driving Cycle (NEDC) for the electric power request, constant loads of 500, 1000, and 2000 W. Values are chosen at $E_{cap} = 4 \cdot 10^6 J$ and operated around 70% of SOE. Chosen value of

constant: $b = 5 \cdot 10^{-5} W^{-1}$, which gives an energy efficiency of 95% at 1000W and 90% at 2000W. Parameters for the vehicle chosen are as follows:

Quantity	Symbol	Value	Unit
Mass	M	1476 (CV)/785 (CM)	Kg
Frontal area	A_d	2	M^2
Air drag coefficient	C_d	0.3	-
Rolling Resistance	C_r	0.015	-
Wheel radius	ω_r	0.3	M
Final drive ratio	f_r	4	-
Gear ratio	g_r	3.4-2.1-1.4-1.0-0.77	-
Idle speed	ω_i	73.3	Rad/s
Air density	ρ	1.2	Kg/m^3
Gravity	g	9.8	m/s^2

Table 1: Parameters for simulations

5.2 Strategies

Following strategies are undertaken during simulations.

- (1) Conventional Base Line (BL)
- (2) Reduced model vehicle and optimized with DP, DP1, QP and QP1
- (3) Vehicle with Composite materials and optimized with DP, DP1.

5.3 Results and Analysis

5.3.1 Fuel Consumption

Strategy	$P_i=500W$	$P_i=1000W$	$P_i=2000W$
Conventional Vehicle	561.264	593.214	664.241
Reduced model Vehicle	556.157	598.862	661.464
Vehicle with composite materials(CM)	552.210	585.661	657.362
Strategy	$P_i=500W$	$P_i=1000W$	$P_i=2000W$
Reduced model Vehicle(RM)	566.157	589.862	661.464
RM+DP(DP)	546.806	580.549	655.460
RM+CM+DP(DP1)	545.613	580.693	655.434
RM+QP(QP)	546.524	581.140	655.374
RM+CM+QP(QP1)	546.456	581.057	655.259

Table 2: Fuel Consumption in gm

From the tables 2 it is evident that it is beneficial to reduce the weight of vehicle by replacing conventional materials. Use of modified DP proposed in this thesis for energy management is also beneficial.

5.32 Battery storage power

Fluctuations in battery storage power during a cycle are given in figure 2.

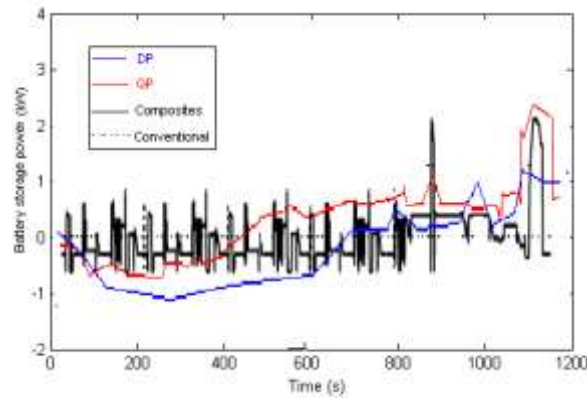


Figure 2: Fluctuations in battery storage power

5.33 Battery state of energy

State of Energy (SOE) of battery is given in fig.3.

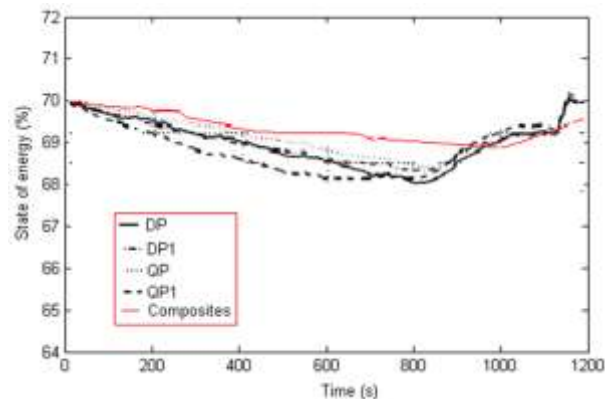


Figure 3: Battery SOE during a cycle.

Figures 2 & 3 show that fluctuations in battery storage power are minimum with composite materials, SOE variation for composite materials also less in comparison to others.

6. Conclusion

Model reductions proposed in this paper proves to be beneficial for efficient energy management and thereby reduction of fuel consumption and exhaust emission. Modified Dynamic Programming proposed can be successfully used in for reduction in fuel consumption. It is also beneficial to replace conventional materials by composites to reduce to reduce the weight and thus reduce fuel consumption.

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