An Online Adaptive Power Management Strategy for Plug-in Hybrid Electric Vehicles

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Abstract. In this paper, an online power management strategy for plug-in hybrid electric vehicles (PHEVs) is presented. The suggested strategy has little dependence on priori knowledge of the driving cycle and future power demands. It needs just the driving duration. In this method, instead of solving a complex mathematical problem, some physical characteristics of the PHEV's components such as the engine fuel consumption power curves are used. These curves are discretized to multiple linear zones. The zones selection is dependent on the state of charge (*SOC*) level of the energy storage system. For each zone, an instantaneous optimal problem is solved. Moreover, this strategy is adapted by considering the previous driving cycle during distinct time periods. Finally, a parallel PHEV is simulated in ADVISOR environment and the results are compared with another method.

Key words

Adaptive control, Fuel economy, Incremental fuel cost, Plug-in hybrid electric vehicle (PHEV), Power management strategy (PMS).

1. Introduction

Nowadays, vehicles fuel economic and environmental problems have an important role in government's decisions and public ideas. Therefore, hybrid electrical vehicles (HEVs) and plug-in HEVs (PHEVs) are introduced as one way to reduce the pollution and increase the fuel efficiency.

PHEVs are the new generation of HEVs that can be plugged into an electricity outlet for charging the energy storage system. Therefore, this type of vehicles consumes less fuel and their emissions are less than HEVs at least in the city area. As a comparison to the non-plug-in hybrids, a plug-in hybrid offers [1]:

- 25%-55% reduction in NO_x
- 35%-65% reduction in greenhouse gases
- 40%-80% reduction in gasoline consumption

The main differences between a PHEV and a HEV are the drive train control strategy and the battery energy capacity design [2]. The fuel consumption of PHEVs is affected very much by the performance of their components and power management strategy (PMS). To achieve maximum fuel profits for PHEVs, many PMSs are presented. Based on mathematical behaviour and structure of the control strategies, PMSs are divided into two groups: Rule based strategies and optimization based strategies [3].

Rule based PMSs operate based on a set of rules that is defined by the system. These strategies optimize the performance of each component individually. Therefore, they are not able to find the global optimum points [3]. However, due to easy performance and low mathematical burden, rule base PMSs are so attractive. Many PMSs are presented recently, covering heuristic rule based approaches [2],[4]-[6] as well as fuzzy rule based strategies [7]. A novel rule based PMS for the PHEVs that focuses on all electric range and charge depletion range operations is presented in [2]. An engine on-off rule based control strategy considering position of acceleration pedal is proposed in [4]. A new heuristic solution for parallel and series-parallel PHEV is proposed in [5]. A rule based fuzzy logic control strategy for a parallel hybrid electric city public bus is proposed in [7].

Optimization based controllers are used to develop an optimal PMS for PHEVs by minimizing a cost function. Usually this type of PMSs is more accurate than the rule based PMSs, but they have more mathematical burden and need the future driving cycle information. Therefore, global optimization methods are non-causal and almost impractical. However, there are a lot of researches on attaining this information from new transportation and geographical systems like GPS and GIS [8]-[9].

One of the most interesting global optimization PMSs is dynamic programming (DP) [10]-[11]. DP is very time consuming and has complex mathematics. Therefore, authors are proposed two-scale DP that can reduce mentioned problems [12]-[14].

Many researches are done for attaining new and better PMSs. The equivalent fuel consumption strategies (ECMS) are proposed by [7],[15]-[16].

Adaptive controllers are being studied as they show the most promise for optimizing the components in a PHEV for maximum performance in real time [8],[17]. An adaptive PMS can optimize itself in real time based on available vehicle parameters and new conditions like driving cycle [3]. For example in this paper, it is assumed that every driving cycle is made up from different small urban and highway samples. Therefore PMS can optimize itself by recognition of its mode from the previous driving cycle conditions.

The proposed PMS has slight mathematic calculations and needs just the estimation of the driving duration to design the reference *SOC*. Therefore, the proposed method can be applied online and it is compatible with different driving cycles.

The PMS that is presented in this paper, is an online adaptive PMS based on physical insight in to PM problem. The concept of this paper is inspired from the concepts of [18] and ECMS method. In this method for the power management of a parallel PHEV, instead of solving complex mathematical problems, the physical characteristics of PHEV's components such as the engine fuel consumption curves are used.

This paper is organized as follows. An adequate vehicle model is presented in Section 2. The background of the proposed PMS is discussed in section 3. The problem formulation for the PMS is given in Section 4, and the main stem of strategy is explained in Section 5. In section 6 an adaptive control strategy is discussed and in 7, the reference *SOC* as a guide for the battery *SOC* is introduced. The simulation results are presented in section 8. Finally, conclusions can be found in Section 9.

2. VEHICLE MODEL

The focus of this paper is on the parallel PHEV topology. The schematic of this topology is shown in Fig. 1. The components of this structure are discussed as follows.

A. *Internal combustion engine (ICE)*

The fuel consumption rate of an ICE is the function of the engine output power (P_m) and the engine speed as (1), where ω is the engine speed and P_m is the engine power. P_m is always a non-negative parameter.

$$fuel\_rate = f(P_m, \omega) \quad (1)$$

B. *Clutch (CL)*

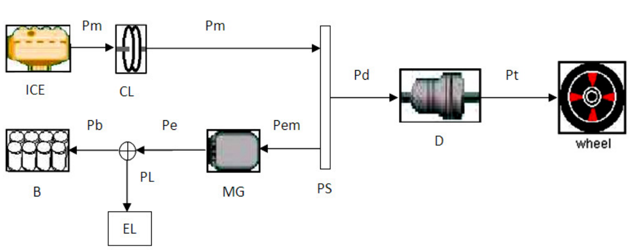

Fig. 1. The parallel PHEV topology

The vehicle engine is engaged to and disengaged from the drive train by its clutch. The clutch will be disengaged during the shifting time of the gearbox, when the engine is off, and when the speed of the clutch becomes lower than the engine idle speed.

C. *Motor/generator (MG)*

There is at least one electrical machine in a PHEV. This electric machine can act as a motor or a generator depends on different conditions. Therefore, the electric machine will be addressed in this paper as motor/generator (MG). The power of MG (P_{em}) is supposed negative in motoring mode and positive in generating mode.

D. *Drive train (D)*

The traction power (P_t) is the required wheels power. For the given vehicle, P_t can be expressed as (2) [3].

$$P_t = \frac{v}{1000}(Mgf_r + \frac{1}{2}\rho_a C_D A_f v^2 + M\delta\frac{dv}{dt} + Mgi) \quad (2$$

where M is the vehicle mass; v is vehicle speed; g is gravity acceleration, ρ_a is air mass density; C_D is the aerodynamic drag coefficient of the vehicle; A_f is the front area of the vehicle; δ is the rotational inertia factor; dv/dt is the acceleration and i is the grade of the road.

Considering P_d as the drive train input power, it can be calculated by (3).

$$P_d = \omega_d \times T_d \quad (3)$$

where ω_d and T_d are the crankshaft speed and torque, respectively.

$$\omega_d = \frac{f_d}{r} v \quad (4)$$

$$T_d = \frac{P_t}{\omega_d \eta_d} \quad (5)$$

where f_d is the drive train ratio, r is the wheel radius and η_d is the efficiency of the drive train.

E. *Power Split (PS)*

The power split is assumed to have no energy losses and provides the following power balance:

$$P_m = P_d + P_{em}. \quad (6)$$

F. *Battery (B)*

The battery is modelled by a voltage source and a series resistance. This resistance represents the battery internal and terminal losses. The *SOC* of the battery is defined as percentage of the remained energy in the battery ($E_s(t)$) to the total theoretical energy capacity of that (E_{cap}) [14].

$$SOC(t) = \frac{E_s(t)}{E_{cap}} \times 100 \tag{7}$$

G. Electric Load (EL)

Electric load (EL) represents auxiliaries such as head lights, radio, etc. The power consumed by EL is called PL. For simplicity this power is assumed to be constant and equal to 700 W.

3. Strategy Outline

A PMS should supply the total power demand with the highest efficiency [19]. In vehicles, fuel is consumed in the ICE. Therefore the fuel consumption can be reduced by good handling of the engine. Hence, this paper has a lot of attention to the ICE characteristics.

The ADVISOR model SI41 engine fuel curves for different speeds are shown in Fig. 2. Each curve is linearized and discretized into several zones and each zone is an operation area for the ICE. In this paper, each curve is divided into 11 zones.

Typically, the slope of each zone (λ_i) is constant, where *i* indicates the zone number. λ_i represents the extra fuel mass flow to produce a small amount of mechanical power by the engine.

$$\lambda_i(P_m, \omega) = \frac{\partial f(P_m, \omega)}{\partial P_m} \tag{8}$$

Fuel consumption rate can be expressed for each zone as (9) where f_{0i} indicates the fuel usage for initial point for zone *i* and N_f is the number of zones.

$$f_i(P_m, \omega) \approx f_{0i}(\omega) + \lambda_i(P_m, \omega) \times P_m \qquad i = 1,2,\ldots,N_f \tag{9}$$

4. Problem Formulation

After choosing the proper zone, the proper ICE operation point in the chosen zone is defined. This point is one with the lowest fuel consumption. Therefore, a cost function is defined and minimized. This function is inspired by ECMS method. In ECMS method, an instantaneous cost function is defined for the equivalent fuel minimization. (10) explains this cost function where $J(t)$ is the equivalent fuel consumption, $f(P_m)$ is the real fuel consumption, H_l is the low heating value of the fuel, and s is the equivalent factor that depends on the driving cycle and efficiency of the power train components [16].

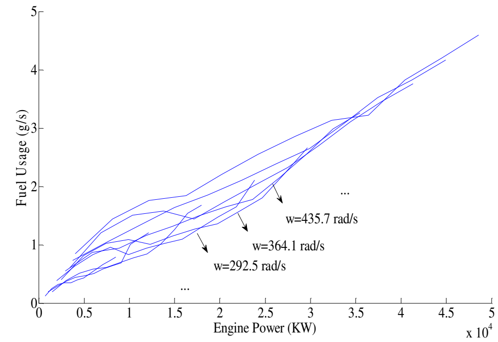

Fig. 2. Fuel map characteristic for ADVISOR SI41 engine

$$J(t) = f(P_m) - \frac{s}{H_l} P_{em} \tag{10}$$

In this PMS, ratio of the equivalent factor and H_l, is considered equal to slope of the chosen operation zone (λ_f). For each zone (i), there is a certain slope called λ_{fi}. Moreover, in order to have only one variable, P_m can be replaced from (6). Therefore, (10) is rewritten as:

$$J(t) = f(P_{em} \mid P_d, P_l, \omega) - \lambda_{fi} P_{em} \tag{11}$$

By two control variable (P_{em} and S), the ICE and MG are manipulated. P_{em} is power of the MG in mechanical side and S is a binary variable that defines the ICE on or off mode. When S is *1*, ICE is on, otherwise it is off.

The results must satisfy the limits. These limits are as follows:

$$P_{em\_\min}(t) \le P_{em}(t) \le P_{em\_\max}(t) \quad \forall t \in [0, t_e] \tag{12}$$

$$P_{s\_\min}(t) \le P_s(t) \le P_{s\_\max}(t) \quad \forall t \in [0, t_e] \tag{13}$$

$$Zone_{\min}(t) \le Zone(t) \le Zone_{\max}(t) \quad \forall t \in [0, t_e] \tag{14}$$

$$SOC(t_e) \approx SOC_L \tag{15}$$

$$SOC(t) \ge SOC_L \quad \forall t \in [0, t_e] \tag{16}$$

However, the ICE is allowed to operate in higher zones than the optimal area if the *SOC* is lower than SOC_L or when the trajectory is missing. These bounds can be defined by design engineers or by mathematical optimization methods.

5. Online Strategy

In this paper, a novel PMS for parallel PHEVs is proposed. In this strategy, just the trip duration is required. This duration can be easily estimated by the vehicle driver or by information systems [19]. Therefore, this PMS do not need a lot of priori information and can be performed online.

In section IV, S is introduced as a control variable with two situations. First consider the situation with $S=1$. When the engine speed is more than its idle speed and $S=1$, the engine will be on. The PMS in this situation is discussed as follows.

In this paper, a reference SOC (SOC_{ref}) is considered as a guide for SOC that can guaranty the proper SOC variation. Therefore, when SOC is lower than SOC_{ref}, then ICE should be operated in the high power area. Otherwise, the ICE operates in the lower power points. In the each iteration of the control strategy, the engine operation zone is allowed to change just one unit. To avoid fast changing in the ICE operation points, ICE continue to operate several seconds in the chosen zone.

In each iteration, an optimal Lagrange multiplier (λ^*) is calculated and used for the proper zone selection. λ^* is a limited parameter and its upper and lower bounds are depended on the ICE characteristics.

The operation zone is shifted when slope of the adjacent zone in proper direction is close to λ^* rather than slope of the present zone. λ^* is calculated by a system that is shown in Fig. 3.

The input signal of proportional integrator (PI) controller is multiplied by -1 if slope of the adjacent zones reduced with power increase. Therefore, λ^* is equal to

$$\lambda^* = \lambda_0 + K_P.e(t) + K_I.\int_0^t e(v)dv \qquad (17)$$

where λ_0 is an initial guess. Selecting the parameters K_P and K_I for a small closed-loop bandwidth allows for a tracking error between the actual SOC and SOC_{ref}.

The proper initial value for λ^* (λ_0), is slope of the most optimal zone. With this selection, the ICE operates near the efficient zone in start of the trip. Appropriately, tuning of the parameters K_P and K_I is described and analysed in [20].

After the proper choosing zone, the cost function (10) should be minimized. Also, the limits (12)-(16) should be satisfied. P_{em} and P_m are obtained from solving (10) and (6).

S will be zero in the following situations:

- If SOC of the battery is more than SOC_L and at the same time the MG and batteries can provide enough power for traction. In other words, if (18) and (19) are satisfied.

$$-P_d \geq P_{em\_\min} \qquad (18)$$

$$\frac{-P_d}{\eta_{mm}} - P_L \geq P_{b\_\min} \qquad (19)$$

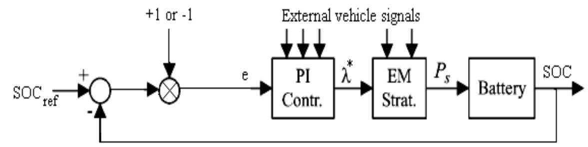

Fig. 3. Feedback diagram for estimating λ^*

- In the regenerative braking mode, if the ICE is off and the kinetic energy of the wheels is captured by the MG. It is assumed that just 60% of this energy can be regenerated [18].

6. Adaptive Online Strategy

Usually, in a highway the average demanded power is more than urban driving cycles and the ICE does not need frequent starting and stopping. Therefore, this paper suggests, the batteries should be charged in highways and discharged in the urban driving cycles. Therefore, the proposed PMS is modified as follows:

In highway driving cycles, the ICE operation points are shifted from present zone to the adjacent zone with higher power. In this condition, if SOC is lower than SOC_{ref}, the ICE should be on and charge the batteries. In urban driving cycles, the ICE operation points are shifted from present zone to the adjacent zone with lower power.

The driver can define the driving cycle type, manually. However, the PMS uses a new method for this purpose. Each driving cycle can be divided into several small highway and urban cycles. Therefore, the driving cycle type is defined for the near future considering its type in the recent past. If the average speed in the recent past period is greater than a specific speed, then the next period should be considered as highway, otherwise it is urban. This specific speed is defined by trial and error.

7. Reference SOC (SOC_{REF})

SOC_{ref} is required as a guide for SOC that has essential role in choosing the proper zone. The SOC_{ref} is considered as a straight line from SOC_H at beginning of the trip to SOC_L at its end. However, if the battery SOC reaches to SOC_L before end of the trip, then SOC_{ref} will be switched to the horizontal line with SOC_L value. These two situations are shown in Fig. 4, and Fig. 5.

8. Simulation Results

The proposed PMS is simulated in the ADVISOR environment for 10 repeats of several driving cycles. The results are compared with a heuristic rule based PMS that is proposed in [6]. The simulated vehicle's parameters are presented in table I. The components of this PHEV are as follows: SI41 engine, 28 Ah NiMH batteries, and an AC electric machine with 59 kW peak power.

Simulation is done for the seven normal driving cycles and five combined driving cycles. These five driving cycles are combined from different highway and urban cycles. The average fuel consumption is used for comparison.

A comparison between the proposed adaptive online strategy and the rule based strategy proposed by [6] for 10 repetitions of the seven normal driving cycles, is given in table II. The proposed PMS method has 3.86% less fuel consumption than the rule based strategy considering the simulation results.

The simulation results for NEDC driving cycle is shown in Fig. 6. This driving cycle is shown in Fig. 7. In this strategy, the limitation in the engine start and stop time is not considered. But this condition is similar for all compared strategies. The ICE operation points for these strategies are shown in Fig. 8, and Fig. 9. The ICE operation points are in the higher efficiency areas for the proposed PMS strategy.

Effect of the proposed adaptive strategy that has been explained in section 6 is illustrated in table III. The adaptive PMS has 4.59% less fuel consumption than the compared rule based PMS and 3.7% more fuel reduction than the non-adaptive PMS.

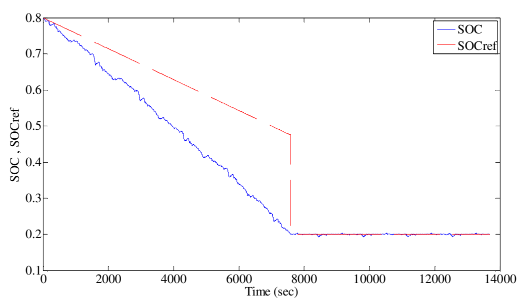

Fig. 4. *SOC* and SOC_{ref} for 10 cycles of UDDS

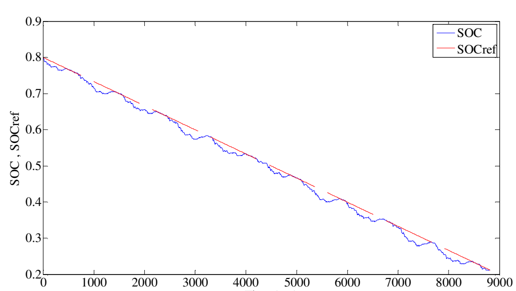

Fig. 5. *SOC* and SOC_{ref} for 10 cycles of INDIA_ HWY

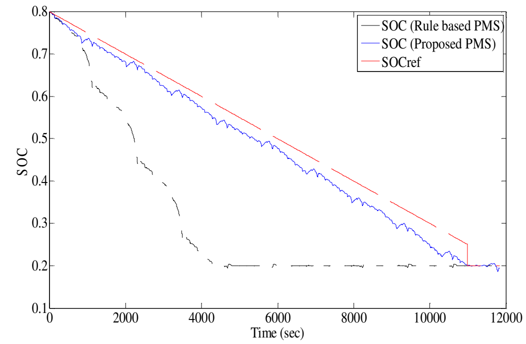

Fig. 6. Simulation *SOC* results for 10 NEDC driving cycles

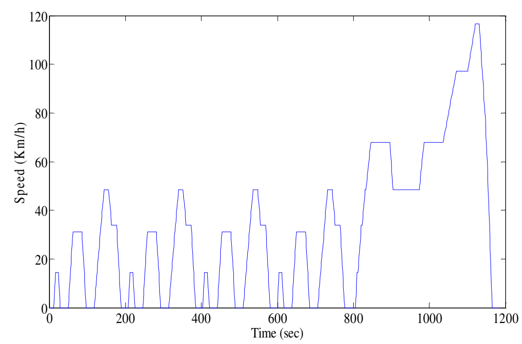

Fig. 7. NEDC driving cycle

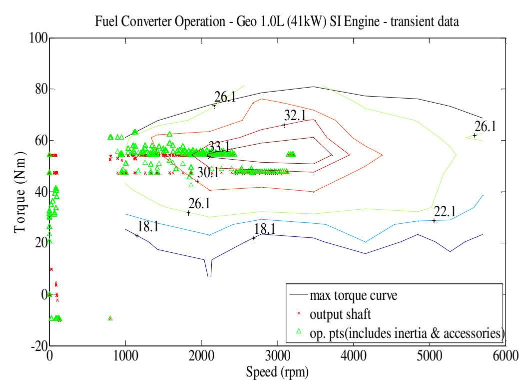

Fig. 8. Engine operating point for the proposed PMS in 10 NEDC

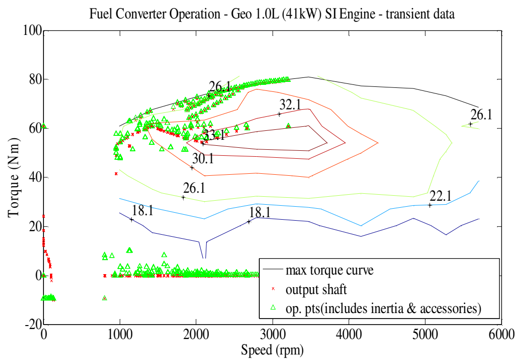

Fig. 9. Engine operating point for the rule based PMS in 10 NEDC

Table I. Parameters of the simulated vehicle

Quantity	symbol	value	unit
Vehicle mass	m	1400	Kg
Front area	A_d	2.0	m^2
Air drag coefficient	C_d	0.3	–
Rolling resistance	C_r	0.015	–
Air density	ρ	1.2	Kg/m^3
Gravity	g	9.8	m/s^2
Wheel radius	ω_r	0.3	m
Upper *SOC* level	SOC_H	0.8	–
Lower *SOC* level	SOC_L	0.2	–
Gear ratios	g_r	13.45_7.57_5.01_3.77_3.01	–

Table II. Fuel consumption results for 7 normal driving cycles.

Cycle (10 repetitions for each one)	Fuel usage for Proposed PMS (L/100Km)	Fuel usage for rule based PMS [6] (L/100Km)
Cyc_EUDC	2.1	2.4
Cyc_FTP	4.2	4.3
Cyc_HWFET	3.3	3.5
Cyc_India_urban_sample	5.2	5.2
Cyc_India_hwy_sample	2.9	3
Cyc_NEDC	3.5	3.7
Cyc_UDDS	3.7	3.8
Average	3.56	3.7

Table III. Fuel consumption results for 5 combined driving cycles (U is urban and H is highway).

Driving Cycle	Fuel usage for rule based PMS [6] (L/100Km)	Fuel usage for non-adaptive PMS (L/100Km)	Fuel usage for adaptive PMS (L/100Km)
(India) H_U_H_U	2.2	2.2	2.1
(India) U_H_H_U	2.2	2.2	2.1
(India) U_H_U	1.6	1.6	1.5
(India) H_H_U_U	2.2	2.2	2.1
UDDS_HWFET_U DDS (2cycle)	2.7	2.6	2.6
Average	2.18	2.16	2.08

9. Conclusions

In this paper an adaptive online concept for power management methods in a parallel PHEV configuration is presented. This concept provides not only a mathematical solution to the PM problem, but also the physical explanation behind the PMS. Due to its low computational requirement, an online vehicle implementation is applicable. Recognition of the driving cycles makes this strategy a powerful and compatible PMS for different driving cycles.

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