A Heuristic power management Strategy for Plug-in Hybrid Electric Vehicles

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Abstract— **In this paper, a rule based power management strategy for a plug-in hybrid electric vehicle is presented. The vehicle engine map is divided into several areas and the engine is controlled based on the demanded power and the battery state of charge. A new proposed strategy is designed in such a way that the engine operates in the efficient area without sacrificing the vehicle performances. Moreover, it is very simple and can be applied using a low cost processor. The proposed strategy is simulated in the ADVISOR environment. The simulation results indicate that the fuel efficiency is improved by using the proposed strategy.**

Keywords- Fuel consumption reduction, Plug-in hybrid electric vehicle (PHEV), Power management strategy (PMS).

I. INTRODUCTION

Nowadays, vehicles fuel economy and environmental issues have an important role in government's decisions and public ideas. Conventional vehicles have high fuel consumption and emission. Therefore, other topologies such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) are introduced. The EVs are cleaner than other vehicle topologies; however, they have limited battery capacity and the battery lasts for few years. The HEVs are cleaner and more efficient than the conventional vehicles. These vehicles normally have two power sources that supply the traction power to the wheels. However, they do not use the external electric energy resources. To solve this problem, plug-in hybrid electric vehicles (PHEVs) are introduced. The PHEVs can be plugged into the power grid or residential photovoltaic system [1]. Therefore, this type of vehicles consumes less fuel and their emission is less than HEVs, at least in the city areas. In comparison to the non-plug-in hybrids, a PHEV offers [2]:

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

The main differences between PHEVs and HEVs are the control strategy and the battery energy capacity [3]. The power management strategy has important effects on the PHEV fuel consumption. Therefore, many control strategies are proposed for the PHEVs. These strategies are divided into two groups: Rule based and optimization based strategies [4].

The rule based methods are causal and their mathematics is simple. Hence, they can be implemented by a normal processor. These strategies usually have several control modes such as the full electric mode (EV), charge depletion (CD) mode, and charge sustaining (CS) mode [4]. These modes are shown in Fig. 1. During the EV mode, the engine is off and the motor supplies the traction power. Therefore, the EV mode is suitable for the low distances in the urban driving cycles. In the CD mode, the engine and motor can operate simultaneously. In this mode, the battery state of charge (SOC) is decreased from its initial SOC to the SOC low state (SOC_L). The strategy is switched to the CS mode, when the SOC reaches to SOC_L. In this situation, the SOC level should be maintained around SOC_L. In this condition, the engine becomes the primary power source, and the motor is used as the secondary source.

A novel rule based PMS for the PHEVs that focuses on all electric range and charge depletion range operations is presented in [3]. An engine on-off rule based control strategy considering the acceleration pedal position is proposed in [5]. A new heuristic solution for parallel and series-parallel PHEV is proposed in [6]. In this paper, the energy management optimizes engine operational efficiency while maintaining battery state of charge. A rule based fuzzy logic control strategy for a parallel hybrid electric city public bus is proposed in [7].

Usually, the optimization based strategies are more accurate but more complex than the rule based strategies. The mathematics of these strategies is complicated and often requires the priori driving cycle information. In order to optimize the problem in this method, a cost function is defined and minimized. This function is usually the fuel consumption or the emission of the vehicle. The optimization group includes a wide spectrum of different methods such as the static optimization, numerical optimization, equivalent consumption minimization strategy (ECMS), and analytical optimization methods [8].

One of the most interesting global optimization strategies is dynamic programming (DP) [9]-[10]. DP is very time consuming and has heavy mathematics. Therefore, authors propose two-scale DP to diminish these problems [11]-[13].

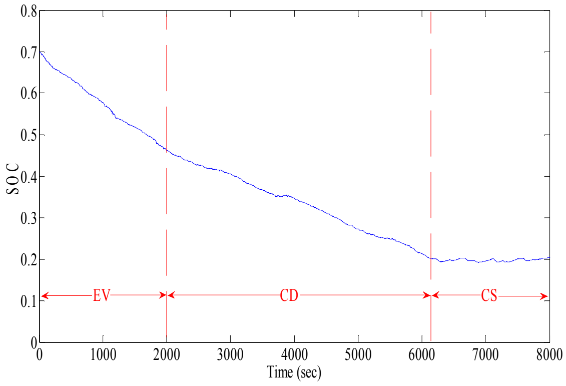

Fig. 1. PHEV operation modes

Many researches are carried out to achieve new and better strategies. A stochastic dynamic programming to optimize the PHEV power management over a distribution of drive cycles, rather than a single cycle by using Markov chain is used by [14]. The equivalent fuel consumption strategies (ECMS) are proposed by [15]-[16].

A heuristic rule based strategy for the PHEVs is proposed in this paper. The proposed strategy just requires the engine maximum power and the thresholds of its efficient area. Therefore, it can be applied real time on different PHEV topologies.

This paper is organized as follows. An adequate vehicle model is presented in Section II. The proposed power management strategy is introduced in section III. The simulation results are presented in section IV. Finally, conclusions are given in Section V.

II. VEHICLE MODEL

The focus of this paper is on the parallel PHEV topology. The schematic of this topology is shown in Fig. 2. In this research, dynamics of the systems with low frequency (lower than one second) are ignored as they have small effects on the fuel consumption of the PHEV. 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_{en} is the engine power. P_{en} is always a non-negative parameter.

$$fuel\_rate = f(P_{en}, \omega) \quad (1)$$

B. CLUTCH (CL)

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.

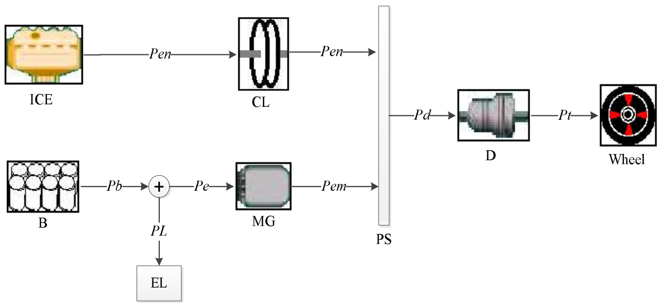

Fig. 2. The parallel PHEV topology

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).

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].

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

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 input power to the drive train, 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:

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

F. BATTERY (B)

The battery is modeled 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 the percentage of the remained energy in the battery ($E_s(t)$) to the total theoretical energy capacity of that (E_{cap}) [17].

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

G. ELECTRIC LOAD (EL)

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

III. STRATEGY OUTLINE

This paper proposes a rule based power management strategy with two control modes (charge depletion (CD) mode, and Charge sustaining (CS) mode). Usually, the electricity is cheaper than the gasoline (four times in USA [17]). Therefore, it is essential that the PHEV's energy storage is discharged before the end of the trip. In the CD mode, the charge of the battery is discharged to the predetermined SOC. Then CS mode is commenced. These control modes are described as below:

A. CD MODE

Both ICE and MG can operate in this mode simultaneously, but the ICE should not charge the batteries. The batteries can be charged just by the regenerative braking as there are some losses in the electric system and the system efficiency is lower than 100%. Consequently, the energy losses are increased if the fuel energy is converted to electricity, whereas the external stored electric energy is available.

The map of the SI41 engine (spark ignition engine with 41 kW maximum power) is shown in Fig. 3. In this figure, $P_{max\text{-}opt}$ and $P_{min\text{-}opt}$ are the optimal upper and lower thresholds of the ICE.

When the ICE speed is lower than its idle speed, the clutch is disengaged and the ICE is off. For higher ICE speed values and P_d within the thresholds, the ICE provides the traction power. The ICE operates on the $P_{max\text{-}opt}$ points if the demanded power is higher than $P_{max\text{-}opt}$ and the rest is provided by the MG. For the demanded traction power lower than $P_{min\text{-}opt}$, the ICE should be off. These rules are summarized in (8)-(10), where P_d is the demanded power and P_{en} is the ICE power.

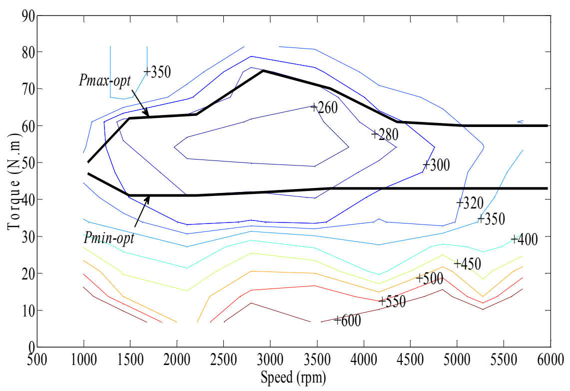

Fig. 3. SI41 engine specific fuel consumption map in the CD mode (g/kWh)

$$P_d \geq P_{max-opt} \rightarrow P_{en} = P_{max-opt} \tag{8}$$

$$P_{min-opt} \leq P_d < P_{max-opt} \rightarrow P_{en} = P_d \tag{9}$$

$$P_d < P_{min-opt} \rightarrow P_{en} = 0 \tag{10}$$

B. CS MODE

In this mode, the battery SOC should be maintained around SOC_M that is shown in Fig. 4. In this paper, an engine on-off power management strategy is used for controlling the CS mode. This control strategy is dependent on the battery SOC. This strategy is shown in Fig. 4 and Fig. 5 and described as follows.

The SOC permissible area is shown in Fig. 4. SOC_M is a reference value that the battery SOC should be maintained around it. SOC_L and SOC_H are the lower and upper thresholds of this area. SOC_{ML} is the average of SOC_M and SOC_L and SOC_{MH} is the average of SOC_M and SOC_H as given in (11) and (12), respectively.

$$SOC_{ML} = \frac{SOC_M + SOC_L}{2} \tag{11}$$

$$SOC_{MH} = \frac{SOC_M + SOC_H}{2} \tag{12}$$

An ICE map is shown in Fig. 5, where P_{max}, $P_{max\text{-}opt}$, $P_{min\text{-}opt}$ and P_m are the ICE maximum power, the upper and lower thresholds of the ICE optimal area, and the average of the $P_{max\text{-}opt}$ and $P_{min\text{-}opt}$, respectively. It is evident that P_m is more efficient than $P_{max\text{-}opt}$ and $P_{min\text{-}opt}$.

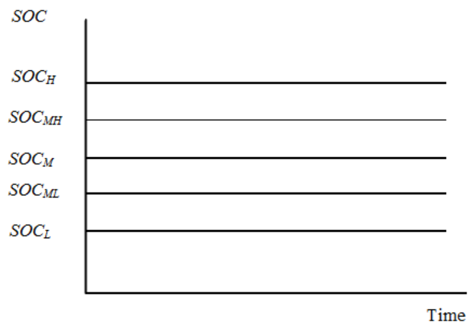

Fig. 4. The battery SOC area in the CS mode.

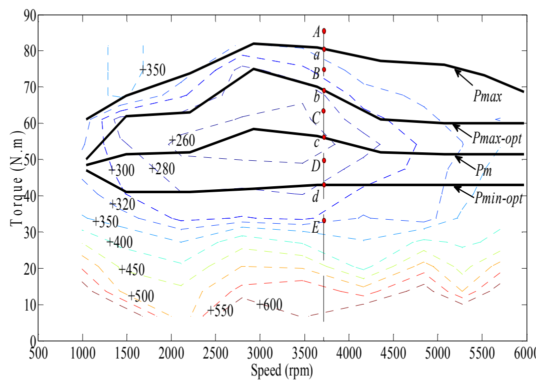

Fig. 5. The SI41 engine operation area in the CS mode.

1. If the requested traction power is greater than the engine maximum power (represented by point *A* in Fig. 4), and the battery *SOC* is lower than SOC_L, the engine should be operated at maximum power (point *a*). Otherwise, if *SOC* is greater than SOC_L, the engine should be operated at point *b* to provide its maximum optimal power. The rest is supplied by MG and drown from the batteries. These rules are summarized in (13)-(14).

$$P_d = A, SOC \le SOC_L \rightarrow P_{en} = a \quad (13)$$

$$P_d = A, SOC > SOC_L \rightarrow P_{en} = b \quad (14)$$

2. If the commanded traction power is lower than P_{max} but higher than $P_{max\text{-}opt}$ such as point *B* in Fig. 4, and the battery *SOC* is lower than SOC_L, the ICE produces its maximum power (point *a*). The battery will charge until it reaches to SOC_{ML} as (11). The SOC_{ML} is selected to avoid the frequent jumping of the engine operating points. For *SOC* between SOC_L and SOC_H, the ICE operates in point *b* (the highest power in the optimal area). Otherwise, for *SOC* greater than SOC_H, the ICE operates at point *b*, until *SOC* descends to SOC_M. However, *SOC* can be arisen above SOC_H if the brake energy is regenerated in the regenerative braking mode. These rules are summarized in (15)-(17).

$$P_d = B, SOC < SOC_L \rightarrow P_{en} = a - until: SOC = SOC_{ML} \quad (15)$$

$$P_d = B, SOC_L \le SOC \le SOC_H \rightarrow P_{en} = b \quad (16)$$

$$P_d = B, SOC > SOC_H \rightarrow P_{en} = c - until: SOC = SOC_M \quad (17)$$

3. If the driver commands a power that falls between $P_{max\text{-}opt}$ and P_m, and *SOC* be lower than SOC_L, the ICE should operate at point *b*, and charge the batteries until *SOC* rises to SOC_M. For *SOC* higher than SOC_L and lower than SOC_H, the ICE produces the demanded power (point *C*). Otherwise, for *SOC* greater than SOC_H, the ICE should be operated at the point *c* until *SOC* reaches to SOC_M. These rules are as follows.

$$P_d = C, SOC < SOC_L \rightarrow P_{en} = b - until: SOC = SOC_M \quad (18)$$

$$P_d = C, SOC_L \le SOC \le SOC_H \rightarrow P_{en} = C \quad (19)$$

$$P_d = C, SOC > SOC_H \rightarrow P_{en} = c - until: SOC = SOC_M \quad (20)$$

4. If the demanded power is equal to point *D* and *SOC* is lower than SOC_L, the engine should provide its maximum optimal power (Point *b*) until *SOC* rises to SOC_M. If *SOC* falls between the SOC_L and SOC_M, the engine should be operated at point *c*. the engine operates at this point until the battery charge reaches to SOC_{MH}. For *SOCs* between SOC_M and SOC_H, the engine produces the demanded power. Otherwise, for *SOC* greater than SOC_H, the engine operates at the lowest optimal point. These rules are as follows.

$$P_d = D, SOC < SOC_L \rightarrow P_{en} = b - until: SOC = SOC_M \quad (21)$$

$$P_d = D, SOC_L < SOC \le SOC_M \rightarrow P_{en} = c - until: SOC = SOC_{MH} \quad (22)$$

$$P_d = D, SOC_M \le SOC \le SOC_H \rightarrow P_{en} = D \quad (23)$$

$$P_d = D, SOC > SOC_H \rightarrow P_{en} = d - until: SOC = SOC_{MH} \quad (24)$$

5. If the request traction power is lower than the engine's efficient power area, and *SOC* is lower than SOC_M, the engine provides the average optimal power. If *SOC* is between SOC_M and SOC_H the engine operates at point *d*. Otherwise, the engine should be off, until *SOC* descends to SOC_M. These rules are as follows.

$$P_d = E, SOC \le SOC_M \rightarrow P_{en} = c \quad (25)$$

$$P_d = E, SOC_M < SOC < SOC_H \rightarrow P_{en} = d \quad (26)$$

$$P_d = E, SOC \ge SOC_H \rightarrow P_{en} = 0 - until: SOC = SOC_M \quad (27)$$

IV. Simulation Results

The proposed power management strategy is simulated in the ADVISOR environment for seven different driving cycles. The mentioned vehicle model in section II is a general model and ADVISOR is convenient with this model. The results are compared with the results of the rule based strategy that is proposed in [3]. The simulation is performed on a vehicle with parallel topology. The vehicle parameters are presented in table I. Assumed vehicle is a C class car that components of this PHEV are given in table II. A list of the driving cycles is given in table III. Average of the fuel consumption for these cycles is considered as a comparison criterion. The simulation results are given in table III. The fuel saving of the proposed power management strategy is about 2.57% better than the compared control strategy. Therefore, the proposed strategy can save 0.6 liter gasoline in each 100 km more than compared strategy. Moreover, the simulation results for ten consecutive NEDC driving cycles are also discussed. The NEDC driving cycle is shown in Fig. 6.

The engine operation maps for both control strategies are shown in Fig. 7 and Fig. 8. In the conventional strategy, the engine operates in low efficiency areas as shown in Fig. 8. Consequently, the fuel saving of the proposed strategy is more than that.

The *SOC* trajectory for the proposed strategy in ten consecutive NEDC driving cycles is shown in Fig. 9. There are two distinct areas in Fig. 9. The first part of the *SOC* trajectory is CD mode and the second part is CS mode.

The main difference between the two mentioned strategies is in the structure of CS mode. The proposed strategy has more fuel saving. Therefore, the CS mode structure is more suitable in the proposed strategy than the compared control strategy.

The battery and ICE output powers are shown in Fig.10 and Fig. 11, respectively.

Table I. The vehicle parameters

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	0.22	_
Lower *SOC* level	SOC_L	0.18	_
Medium *SOC* level in CS mode	SOC_M	0.2	
Initial *SOC*	SOC_{in}	0.8	_
Gear ratios	g_r	13.45_7.57_5.01_3.77_3.01	_
Electrical load	P_L	700	*Wat*

Table II. The vehicle components

Engine	**SI41-with 41 kW maximum power and 0.34 peak efficiency**
Electric machine	AC59 – with 56 kW maximum power and 0.91 peak efficiency
Battery	NIMH28_OVANIC- with 28 Ah nominal current and 335 V nominal voltage
Transmission	TX_5SPD- with 1.00 peak efficiency

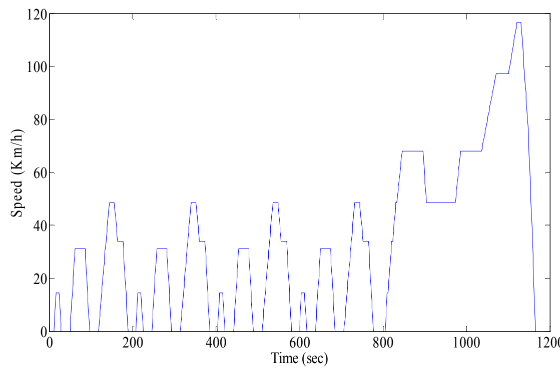

Fig. 6. NEDC driving cycle

Table III. The simulation results

Driving Cycles (ten repeats)	Proposed Strategy	Compared Strategy [3]
	Liter/100Km	Liter/100Km
Cyc_EUDC	3.1	3.1
Cyc_FTP	3.8	3.9
Cyc_HWFET	3.1	3.2
Cyc_India_urban_sample	4.9	5.1
Cyc_India_hwy_sample	2.6	2.6
Cyc_NEDC	3.2	3.3
Cyc_UDDS	3.2	3.3
Average Value	3.41	3.50

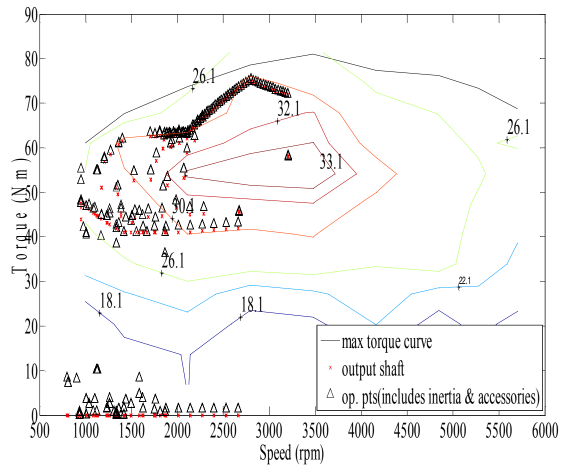

Fig. 7. Engine operating points for the proposed strategy in ten consecutive NEDC cycles

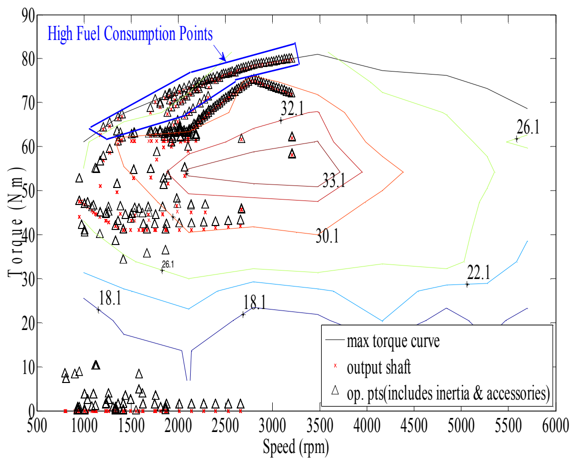

Fig. 8. Engine operating points for the previous control strategy in ten consecutive NEDC cycles

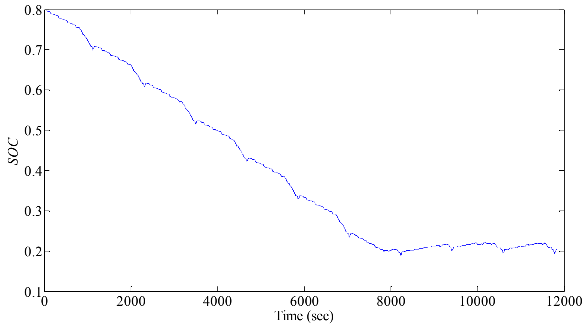

Fig. 9. *SOC* trajectory for the proposed strategy in ten consecutive NEDC cycles

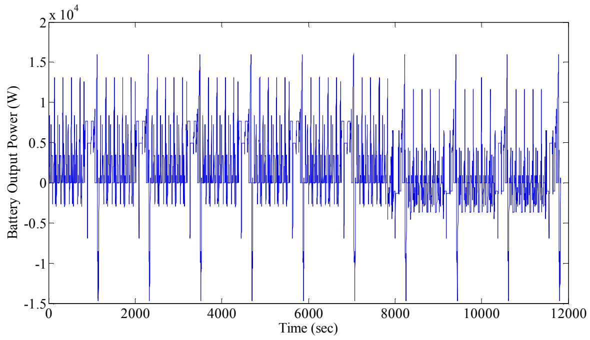

Fig. 10. Battery output power for the proposed strategy in ten consecutive NEDC cycles

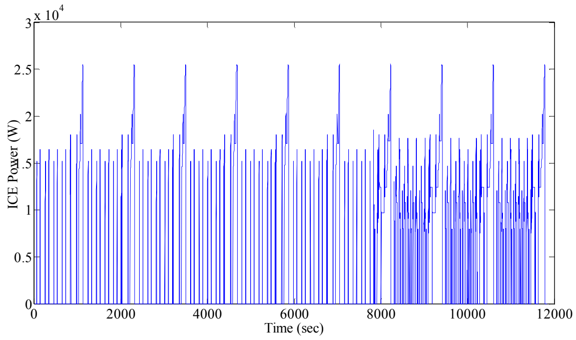

Fig. 11. ICE power for the proposed strategy in ten consecutive NEDC cycles

V. CONCLUSION

This paper presents a rule based power management strategy for the parallel PHEVs. This strategy is very simple and does not need the priori driving information. Therefore, it can be applied practically and has a good performance in the real time applications. The engine is manipulated very well by this strategy. Therefore, this strategy causes considerable reduction in the fuel consumption. The simulation results reveal the proposed strategy has 2.5% more fuel saving than its previous version.

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