HCTL Open International Journal of Technology Innovations and Research (IJTIR)
http://ijtir.hctl.org
Volume 14, April 2015
e-ISSN: 2321-1814, ISBN (Print): 978-1-62951-946-3

ECMS Based Hybrid Algorithm for Energy Management in Parallel Hybrid Electric Vehicles

Vikas Gupta
vikas.gupta@mcia.upc.edu

Abstract

In this paper a model-based hybrid algorithm for energy management in parallel hybrid electric vehicles is presented. The aim is to develop a hybrid algorithm which gives optimal solution for fuel consumption for both online and offline conditions. This algorithm has two parts. In the first part the modes of operation are selected by the help of IF THEN ELSE rules, the selection of mode in which the hybrid electric vehicle is working is done. IF THEN ELSE rules are also used to optimize the fuel consumption by selecting engine to work in high efficiency zone. In the second part the fuel consumption obtained in electric and engine combined mode is further optimized by Equivalent consumption minimization strategy (ECMS) algorithm. The main advantage of this algorithm is that it can do optimization for both online and offline scenarios and this algorithm do not need the prior knowledge of the drive cycle. It gives optimal solution, also, the computational time of this algorithm is very low, the algorithm has very less mathematical complexity, and coding is easy to do

Keywords

Parallel hybrid vehicles, ECMS, IF Then else rules, online scenario, optimization, modes

Introduction

HEVs are broadly classified into two major categories, i.e. parallel and series HEVs [1] [2] [3]. This paper deals with energy management strategy in parallel HEVs since they are the most commonly used and manufactured at present. Parallel HEVs allow downsizing the engine while providing more freedom to satisfy the power demand because series HEVs are driven only by electric traction. In a parallel hybrid vehicle, both the ICE and the EM may work simultaneously [4], since they are coupled to a common axis. The EM may either provide extra power to the powertrain or recover the kinetic energy during braking. The EM is also used in operating regions where the ICE has low efficiency, thus increasing the fuel economy or applied as a generator when the SOC is below a threshold value.

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[1] MCIA Research Center, Universitat Politècnica de Catalunya, Rambla Sant Nebridi 22, 08222 Terrassa, Spain.

This paper deals with the energy management strategy in parallel HEVs, which is based on sharing the load power demand between the vehicle's energy sources, while ensuring optimizing system efficiency. Control strategies used for energy management in hybrid vehicles may be broadly classified into three categories. The first category is classified as rule-based methods, the fuzzy logic method [2] [5] [7] [11] and other heuristic methods [17], belonging to this category, which shows appealing features as low sensitivity to component changes and measurement inaccuracies. The second category uses the equivalent fuel consumption as a cost function. The equivalent fuel consumption comprises the fuel consumption of the ICE as well as that of the other energy sources. Equivalent consumption minimization strategy (ECMS) [13] is the main technique in this category. It is worth noting that the two first groups do not rely on the priori knowledge of the future driving cycle but they provide suboptimal solutions [16]. The third group of methods is based on dynamic programming optimization [4]. However, although this technique provides optimal solutions, it is rather computationally demanding and requires prior knowledge of the driving cycle, which is frequently unknown. There is fourth group of methods known as analytical optimization group; Pontryagin's Maximum Principle(PMP) belongs to this group, this technique also does not give optimal solution.

In this paper a novel hybrid method which combines both IF THEN ELSE and ECMS control algorithms for energy management in parallel HEVs [6] [8] [9] is proposed and its behavior is checked by analyzing two driving cycles [10] [12] [14]. This paper consists of four sections numbered from II to V. In section II parallel hybrid electric vehicle architecture [8] [9] is defined, in section III the hybrid algorithm (IF THEN ELSE + ECMS) is defined. In section IV and V the results and conclusion are presented.

Parallel Hybrid Drive Train

The architecture of a parallel hybrid drive train is shown in figure 1. Parallel hybrid consists of two power sources in the drive train internal combustion engine (ICE) and an electric motor. Both internal combustion engine and an electric motor is joined at an axis in parallel, since speed coupling is used so the speed of motor and engine are sum at the axis. Torque is identical for engine and motor since similar gear boxes are supposed for both engine and motor as shown in equations 1 and 2.

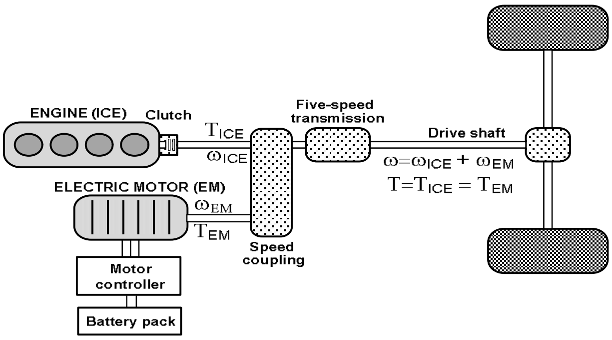

Figure 1 Parallel hybrid drivetrain

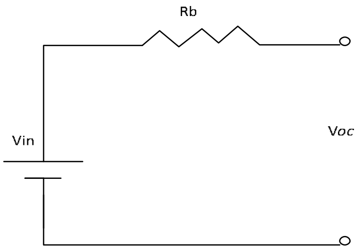

Figure 2 Battery model

$\omega_{total} = \omega_{ice} + \omega_{em}$ (1)

$T_{request} = T_{em} = T_{ice}$ (2)

Where ω_{ice} is the speed of engine and ω_{em} is the speed of electric motor in equation 1.

$T_{request}$ is the total torque at the transmission, T_{em} is the torque of the electric motor and T_{ice} is the torque of the engine as shown in the equation 2. The power requested by the driver is calculated by equation (3) to (7),

$F_{wheel} = Ma_{cc} + \mu Mg\cos A + Mg\sin A + \frac{1}{2} \rho C_D A_{frontal} v^2$(3)

$T_{wheel} = F_{wheel} * r_{wheel}$ (4)

If $T_{wheel} > 0$ than $T_{request} = T_{wheel} / \eta_{trans} * g_r$ (5)

If $T_{wheel} \leq 0$ than $T_{request} = T_{wheel} * \eta_{trans} / g_r$ (6)

$P_{request} = T_{request} * (v / r_{wheel}) * g_r$ (7)

Figure 2 shows a simple battery model. The state of charge (SOC) of the battery is the ratio between the current battery capacity and the nominal full capacity and plays a key role in the performance of hybrid electric vehicles. The power of the battery is calculated as follows,

$$P_{batt} = \frac{V_{oc}^2 - V_{oc}\sqrt{(V_{oc}^2 - 4P_{inv,DC}R_b)}}{2R_b} \quad (8)$$

The battery energy at any time instant *t* is calculated as,

$$E_{batt}(t) = E_{batt}(t_0) - \int P_{batt}(t)dt \quad (9)$$

Note that during charging (-) sign in (9) is replaced by (+). The state of charge (SOC) of the battery may be calculated as,

$$SOC = E_{batt}(t) / E_{batt,\ nom} \quad (10)$$

The values used for SOC and power requested by the driver calculation are shown in Table 1 and Table 2.

TABLE 1: VEHICLE STRUCTURAL PARAMETERS

Parameter	Value
$[SOC_{min}, SOC_{max}]$	[0.2, 0.8] p.u.
Battery type	Lithium-ion
Cell nominal voltage	3.30V
Cell nominal capacity	2.22 Ah
Energy capacity, $E_{batt,\,nom}$	4 kWh, 546 cells 91 in series x 6 sets in parallel
$E_{batt}\ (t_0)$	3.0 kWh
η_{bat}	0.9 p.u.
V_{oc}	300 V
R_b	0.37 Ω
P_{ICE}	[0, 65] kW
P_{EM}	[-50, 50] kW
η_{gen}	0.9 p.u.

TABLE 2: VEHICLE MODELLING PARAMETERS

Parameter	Value
$A_{frontal}$	2.16 m^2
r_{wheel}	0.29 m
M	1500 kg
η_{trans}	0.9
$g_r(1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th})$	15.5, 10.1, 6.8, 5.0, 3.8
C_D	0.26
ρ_a	1.2 kg/m^3
α	0°
μ	0.01

Several constraints were taken into account to ensure an adequate behavior of the vehicle, which are as follows

$$P0_{request} = P_{em} + P_{ice} \qquad (11)$$

$$SOC_{min} \leq SOC\ (t) \leq SOC_{max} \qquad (12)$$

$$0 \leq P_{ice}\ (t) \leq\ P_{ice,max} \qquad (13)$$

$$P_{em,min} \leq\ P_{em}(t) \leq\ P_{em,max} \qquad (14)$$

$$P_{batt,min} \leq P_{batt}(t) \leq P_{batt,max} \qquad (15)$$

If the acceleration or power requested $P_{requested}$ are negative, then the regenerative braking mode (mode 5) is selected

and the energy produced during this mode is delivered to the battery pack, which is expressed as,

$$E_{regen} = \frac{1}{2} \cdot \eta_{bat} \cdot \eta_{gen} \cdot M \cdot (v_1^2 - v_2^2) \qquad (16)$$

v_1 and v_2 being respectively, the initial and final speeds of the applied braking interval. It is assumed that both the battery and motor can recuperate the regenerative braking energy at any time. Figure 3 and Figure 4 respectively shows efficiency maps of internal combustion engine and electric motor used in hybrid model for calculation of energy consumption in each mode for a respective drive cycles.

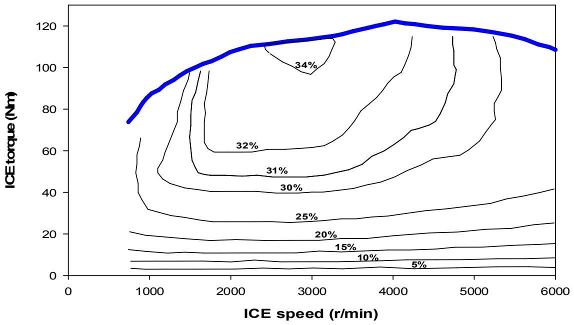

Figure 3: Torque-speed and efficiency map of the 65 kW ICE

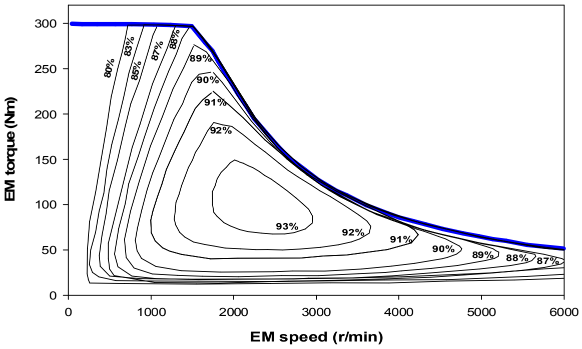

Figure 4: Torque-speed and efficiency map of the 50 kW EM (permanent magnet synchronous motor)

Hybrid Algorithm (If then Else + ECMS)

This paper proposes a hybrid algorithm which combines an IF THEN ELSE with ECMS (Equivalent Consumption Minimization Strategy) for energy management in parallel HEVs.

The hybrid IF THEN ELSE + ECMS algorithm

This paper proposes a hybrid algorithm which combines an IF THEN ELSE control algorithm with ECMS (Equivalent Consumption Minimization Strategy) for energy management in parallel HEVs. The IF THEN ELSE algorithm proposed in this paper deals with three input variables, namely actual vehicle speed, state of charge and acceleration. The output is the operating mode, which has five possibilities as detailed in the following paragraphs. The selection of the actual operation mode (output) is done by the IF THEN ELSE control algorithm, which takes into account the actual values of the input variables. The SOC is limited within the range 0.20 to 0.80 to avoid premature aging of the battery pack and improve battery performance, whereas the initial SOC is supposed 0.75.
Parallel HEVs may work in 5 operating modes,

- **Mode 1**. EM only mode.
- **Mode 2**. ICE only mode.
- **Mode 3**. Hybrid ICE+EM mode.
- **Mode 4**. Charging mode.
- **Mode 5**. Regenerative mode

The IF-THEN-ELSE based algorithm is used to select the instantaneous operation mode as follows,

```
IF acceleration> 0
  IF SOC ≥ 0.55
    IF velocity <30 km/h MODE 1 is selected (motor only)
      ELSE
        IF velocity<60 km/h MODE 2 is selected (ICE only)
          ELSE MODE 3 is selected (ICE + motor)
  IF SOC < 0.55 MODE 4 is selected (battery charging)
IF acceleration< 0 MODE 5 is selected (regenerative mode)
```

The main problem of the rule based control algorithm is that they provide suboptimal solutions and they depend upon intuition. Therefore the equivalent consumption minimization strategy (ECMS) is employed to further optimize the fuel consumption in the hybrid model, i.e. ICE + electrical motor mode (mode3). The ECMS algorithm is an on-line optimization method which attempts minimizing the fuel consumption at every time instance. ECMS is focused to determine the best power sharing between the ICE and the battery to cope with the power demand. To this end, ECMS defines an instantaneous cost function based on the equivalent fuel consumption. This is calculated as the fuel mass flow rate (it is a function of the power delivered by the ICE) plus the equivalent fuel flow rate due to the EM. This latter is a function of the equivalence factor (the factor applied to transform the electric power consumption into the equivalent fuel consumption) and the EM output power among others. The main objective of the ECMS algorithm is to optimize the overall fuel consumption by minimizing the fuel consumed by the ICE. Next equations present the mathematical details involved in the ECMS algorithm. The objective function to be minimized by the ECMS algorithm is given as,

$$J(t)=\int_0^t \dot{m}_{eq}(t)dt=\int_0^t\left[\dot{m}_{ice}(t)+\dot{m}_{battery}(t)\right]dt \qquad (17)$$

where $\dot{m}_{ice}(t)$ is the fuel consumption of the ICE in kWh and $\dot{m}_{battery}(t)$ is the equivalent fuel consumed by the vehicle during battery charging or discharging.

For mode 3, i.e. when the battery is discharging, the equivalent fuel consumed by the battery is,

$$\dot{m}_{battery}(t) = K_{eqf}\cdot P_{batt}/(Q_{lhv}\cdot\eta_{total}) \qquad (18)$$

whereK_{eqf} is the equivalence factor, which acts as a weighting factor for the electric energy. This factor affects the optimum power sharing between the engine and the motor. Q_{lhv} is the gasoline lower heating value and η_{total} is the drive train efficiency. The SOC of the battery is not explicitly considered in the objective function, as described in (17). However, it must be taken into account since the SOC must be maintained within a predetermined range to ensure satisfactory vehicle behavior and adequate battery useful life. To take into account the current SOC value, a feedback adjustment is often applied to the weighting factor K_{eqf} in (18) and (19) as follows,

$$K_{eqf} = EQF\cdot K_p\cdot K_I \qquad (19)$$

Adaptive equivalence factor is used in this hybrid algorithm. For a parallel hybrid configuration, the suggested value of *EQF* is 2.4 whereas K_p and K_I are the gains, whose values are calculated as follows,

$$x_1(t) = \frac{SOC(t) - SOC_{ref}/2}{\Delta SOC/2} \qquad (20)$$

whereSOC_{ref} is set to 27% and ΔSOC is set to 4%. In addition,

$$K_p = 1 - x_1^3 \qquad (21)$$

$$x_2(t) = 0.01 \cdot \left(SOC_{ref} - SOC(t)\right) + 0.99 \cdot x_2(t - \Delta t) \qquad (22)$$

$$K_I = 1 + \tanh(12 \cdot x_2) \qquad (23)$$

Δt being the time step taken during simulations

Table 3 shows the summary of the hybrid algorithm. It is shown that IF THEN ELSE is first used to select the operating mode to improve the overall efficiency. Then, the power requested $P_{requested}$ is calculated for each mode and the ECMS algorithm is applied in mode 3 to obtain a near-optimal solution for fuel consumption.

TABLE 3: SUMMARY OF THE HYBRID ALGORITHM

Mode	**Optimization method**
Mode 1 (EM only)	IF THEN ELSE
Mode 2 (ICE only)	IF THEN ELSE
Mode 3 (ICE + EM)	IF THEN ELSE + ECMS
Mode 4 (Charging)	IF THEN ELSE
Mode 5 (Regenerative braking)	IF THEN ELSE

Results

In this section the behavior of the proposed algorithm is evaluated. Two driving cycles with very different characteristics are analyzed, i.e. the US06 or supplemental FTP driving schedule (represents a driving style with fast speed changes) and the EPA highway fuel economy test cycle (represents highway driving conditions). Main features of both driving cycles are summarized in Table 4.

TABLE 4: MAIN FEATURES OF EPA URBAN AND HIGHWAY DRIVING CYCLES

Parameters	US06	EPA Highway
Distance (km)	12.89	16.51
Sample period (s)	596	765
Time resolution (s)	1	1
Average speed (km/h)	77.9	77.7

Figs. 6 and 7 show the results for the both driving schedules. The results include the speed profile, the power requested, the power provided by both the ICE and EM, and the SOC evolution provided by the hybrid algorithm as well as the instantaneous operating mode.

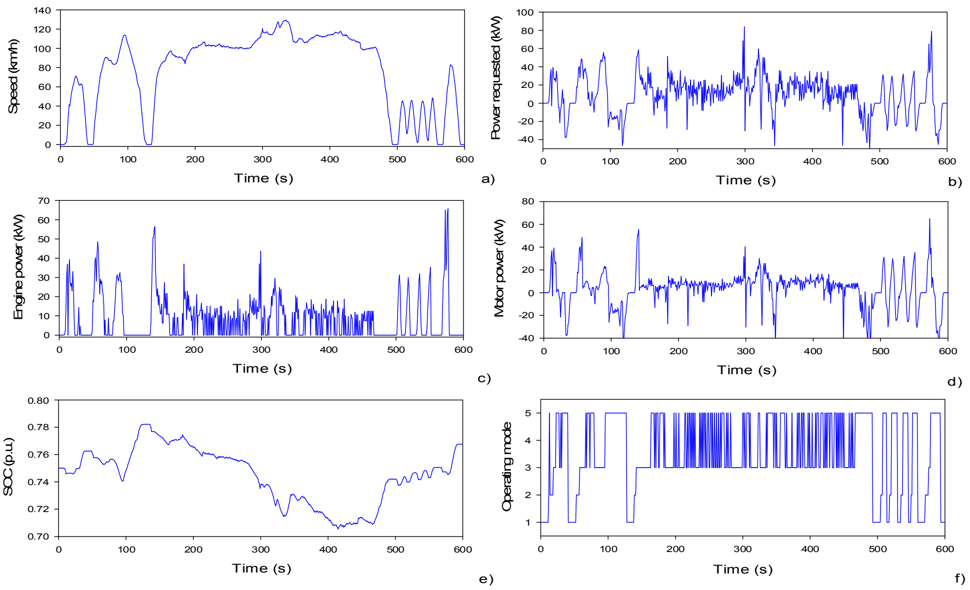

Figure. 6. a) US06 supplemental FTP driving schedule applied to the vehicle modeled in this paper. b) Instantaneous power requested by the driving cycle. c) Instantaneous power delivered by the ICE. d) Instantaneous power delivered by the EM. e) Instantaneous SOC as calculated by the hybrid IF THEN ELSE + ECMS algorithm. f) Operating mode.

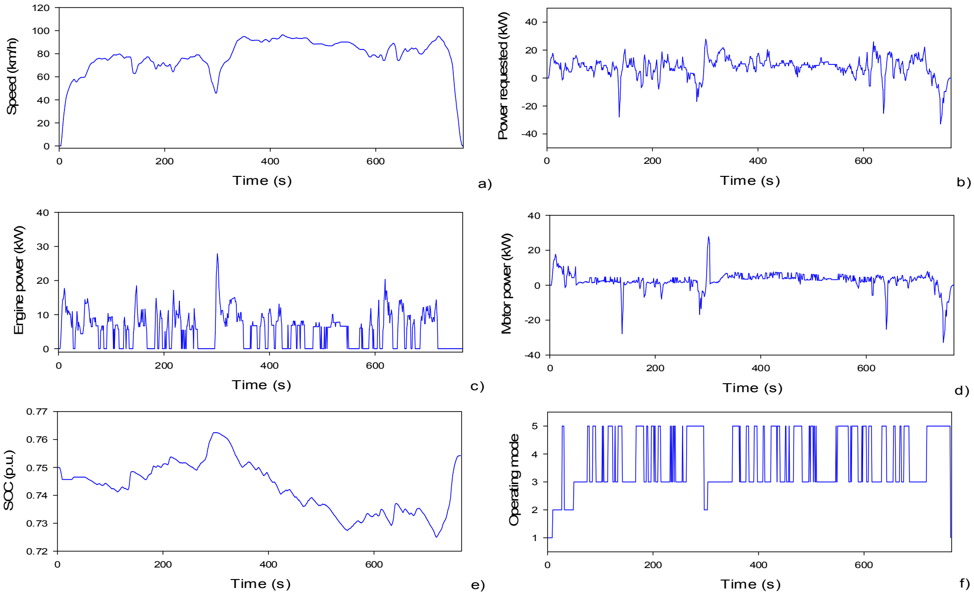

Fig.7. a) EPA highway fuel economy driving schedule applied to the vehicle modeled in this paper b) Instantaneous power requested by the driving cycle. c) Instantaneous power delivered by the ICE. d) Instantaneous power delivered by the EM. e) Instantaneous SOC as calculated by the IF THEN ELSE + ECMS algorithm. f) Operating mode.

Note that the time resolution of both driving cycles shown in Figs. 6 and 7 is one second, which has been taken as the constant sampling time Δt in the calculations presented in next sections. A summary of the results attained in this section are shown in Table 5. It is found that hybrid algorithm leads to **28.5%** better fuel economy in the case of US06 supplemental FTP driving schedule and the hybrid algorithm provides **16.9%** better fuel economy for EPA highway fuel economy driving schedule as compared to ECMS only online algorithms under similar test or driving conditions with all vehicle parameters remain same. These comparative results are a clear evidence of the better performance and strength of the proposed hybrid algorithm over ECMS only for energy optimization in HEVs. Second advantage of this hybrid algorithm that is uses adaptive equivalence factor which makes ECMS used in MODE 3 independent of drive cycle, the equivalence factor remain same for every drive cycle while generally the equivalence factor in ECMS is drive cycle dependent and vary for each drive cycle

TABLE 5: FUEL CONSUMPTION OF THE HYBRID ALGORITHM

Fuel consumption (p.u.)		
Algorithm	US 06	EPA highway
IF THEN ELSE + ECMS	**0.724**	**0.837**
ECMS only	**1.013**	**1.008**

Another interesting aspect of the analyzed algorithm is the computational burden. Table 6 shows the average time required for each analyzed algorithm to calculate each time step (1 second), for both studied driving schedules. The algorithms were programmed in Matlab® and an Intel® Atom™ Processor N450, 1.66 GHz CPU was used.

TABLE 6: COMPUTATIONAL BURDEN OF THE HYBRID ALGORITHM

Computational time (ms)		
Algorithm	US 06	EPA highway
IF THEN ELSE + ECMS	**3.61**	**3.55**

Conclusion

In this paper a hybrid algorithm which combines IF THEN ELSE with equivalent consumption minimization strategy (ECMS) has been proposed and analyzed to optimize the energy consumption in parallel HEVs. To check the performances of such algorithm, two driving cycles have been simulated, i.e. the US 06 or supplemental FTP driving scheduleand the EPA highway fuel economy test cycle. The behavior of the hybrid algorithm has also been compared with ECMS only control. It has been shown that the main advantage the proposed hybrid algorithm is that it provides a better optimized solution regarding fuel economy than other online algorithms which are already present in published literature, while allowing a good management of the battery SOC. In addition, this hybrid algorithm offers both low mathematical complexity and reduced computational burden, so it is easily implementable. It also does not require prior knowledgeof driving cycles, so this hybrid algorithm can be used for both offline and online scenarios.

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