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A Rule-Based Energy Management Strategy for a Series Hybrid Vehicle

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Abstract

In this paper, a Rule-based Control and Energy Management strategy for a Series Hybrid Vehicle is presented. The strategy is based on splitting the power demand between the engine and the battery such that these power sources are operated at high efficiency. The power demand is estimated as the output of a high gain PI (Proportional Integral) controller that controls the longitudinal acceleration of the vehicle. The focus was to improve the fuel economy of the vehicle by suitable power assignment to the power sources.

This power split (assignment) is implemented under a Rule-base frame. The rules depend on the values of selected variables: the power demand itself, the driver's acceleration command and the status of the SOC (state of charge) of the battery. The rules ensure that the engine and the battery operate at high efficiency whenever possible. At high power demand the engine will operate at its maximum rated power.

Simulation results of the proposed strategy showed improvement in fuel economy over the "Thermostat" strategy. An improvement of 11% in the urban cycle and of 6% in the highway cycle have been achieved for a series hybrid vehicle driven by a 40 KW diesel engine and a 60 KW Lead Acid Battery.

1. Introduction

Hybrid vehicles utilize power from more than one on-board source. Generally, the power sources are an internal combustion engine and an electric battery. There are many advantages of hybrid vehicles over conventional ones, of these are: better fuel economy, less environmental pollution, the ability to recover part of the kinetic energy of the deceleration vehicle, and the possibility of operation with alternative fuels and engines. Moreover, hybrid vehicles do not have all the limitations of electric vehicles [1,2].

Different hybrid power train configurations are possible [2,3], however, there are two basic categories: series and parallel. In the series configuration, the engine is not coupled directly to the road wheels, but it supplies power to drive the vehicle through an electric generator and a traction motor. The parallel hybrid configuration, on the other hand, connects both energy sources to the road wheels in parallel. Either is capable of having the vehicle driven with the ability of combining powers at any time [2,3].

In both configurations, the battery can supply power to drive, or aid the engine to drive, the vehicle. It will store the excess energy available from the engine at low wheel power requirements. The battery can also store part of the kinetic energy of the decelerating vehicle through regenerative braking.

The performance and fuel economy of the hybrid vehicle depends heavily on the applied energy management strategy. Few strategies are available in literature [1-6]. For Series hybrid vehicles, the simplest strategy is the "on/off" or "Thermostat" one [1,2]. Under this strategy, the engine will turn on and off based on the SOC status of the battery.

In order to improve the fuel economy of the vehicle, the energy management strategy should cause the vehicle components to operate at high efficiency operating points. This will decrease the power losses and hence improve the fuel economy. Besides, the strategy should not deteriorate the vehicle performance.

Therefore, the main focus in this study has been to develop an energy management strategy in order to improve the fuel economy of a series hybrid vehicle without deteriorating the vehicle performance.

A strategy that is based on splitting the power demand between the engine and the battery is investigated. Under this "Power Split" strategy, the engine and the battery are operated at high efficiency operating points. These operating points are selected based on the efficiency maps of these components. For the engine, a curve that connects the most efficient speed/torque operating points is defined. This gives a range of powers, bounded by a minimum (P_{min}) and a maximum (P_{max}) values, which can be delivered by the engine when it is operated efficiently.

The power demand, in this strategy, is the output of a high gain PI controller that controls the vehicle acceleration. "Gain Scheduling" have been applied here,

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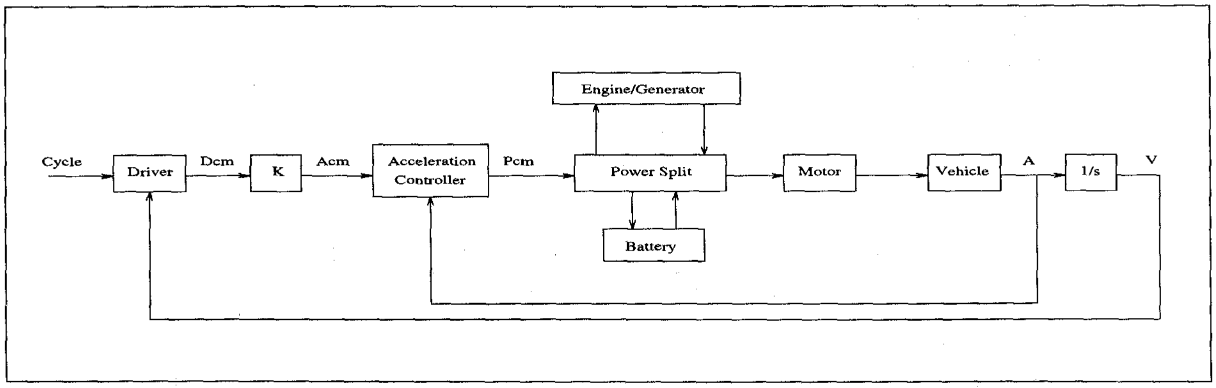

Figure 1: Block Diagram of the Overall Strategy

where two sets of PI coefficients have been used. Based on the acceleration command value, the controller will automatically choose the appropriate gain set. One of these sets is being used for fuel economy evaluation runs, while the other is needed for performance runs.

As mentioned, the strategy has been applied through a rule-based approach. Several rules are used to determine, based on the power demand value, how much power to get from each source if the power demand is positive. Regenerative braking is activated if the power demand is negative. Other rules are used to cause the battery to operate within an efficient range of state of charges and to ensure that some limits are not exceeded. These limits represent the maximum allowable charging and discharging powers of the battery, in addition to the maximum allowable regenerated power.

The Power Split combined with the acceleration controller form the overall energy management strategy proposed here.

2. Longitudinal Acceleration Control

Acceleration control has been considered here in order to improve the vehicle response to the driver demand. The main block diagram of the strategy is shown in Figure (1). The driver will issue a command based on the error between the set-point speed and the actual vehicle speed. This command is interpreted as an acceleration command by linear scaling.

The Acceleration Controller estimates the power needed to let the vehicle follow the driver demand. Based on the acceleration command value, the Gain-Scheduling PI-Controller will automatically choose the appropriate gain set. One of these sets is being used for regular runs, while the other is needed for performance runs where high power is required to satisfy the driver demand.

The output of the acceleration controller is a power demand value. This power demand will be assigned to the engine, the battery, or a combination of both based on the Rule-base as presented in Section (3.2).

3. Energy Management

The aim of an energy management strategy is to minimize fuel consumption of the vehicle for a given driving schedule. In this section, two strategies will be discussed, these are the Thermostat and the Power Split strategies.

3.1. Thermostat

The Thermostat or "On/Off" strategy is a known method which proved to be robust. Under this strategy, the engine will turn on and off based on the SOC status. Two SOC values are chosen by referring to the Efficiency Map of the battery, and such that these two values enclose the most efficient region in the battery operation. The Thermostat strategy has the following logic: if the SOC reaches the lower value, then the engine will turn on and it will operate at its most efficient point. The engine will stay on until the higher SOC value is reached, then the engine will turn off (or run idle), and it will stay off until the lower SOC value is reached; and the cycle repeats itself [1,2].

3.2. Rule-Based Power Split

Power Split energy management strategies has been applied to Parallel hybrid vehicles [3,4]. In this paper, an attempt to apply this concept to the Series hybrid has been conducted. Following is a description of how the strategy works.

Based on the status of the SOC, the power demand and the acceleration command, the power will be assigned to the APU (Engine/Generator), to the battery, or to a combination of both. Figure (2) shows the set of the rules that have been employed.

The strategy uses a "Thermostat" in the background. This has been used mainly to charge the battery in a consistent way.

Based on the status of the Thermostat, the assignment of power is determined as follows; if the lower SOC is reached, then the APU will be on and the default output power of the APU is the optimal operating point (maximum efficiency) power. However, if more power than P_{min} is needed, then the APU will supply it. If the power demand exceeds P_{max} then both sources will supply power to satisfy the demand.

On the other hand, if the higher SOC is reached, then the default output power from the APU is zero (engine is idle). However, if the power demand exceeds the P_{min} limit , at any moment, then the APU will start delivering power. The battery will satisfy the power demand if the latter is less than P_{min}, in addition, the battery will help the APU if the power demand is more than P_{max}. The engine will not be shut off under this strategy, it will be idle if no APU power is needed. This causes some extra fuel consumption, but there are advantages of this by limiting engine cycling on and off; moreover, the engine will be warm all the time which is better for emissions.

A high acceleration command means that the driver is asking for high power. In this case the engine will operate at its maximum rated power in order to satisfy the demand.

Furthermore, the power. to be charged or discharged from the battery, at any moment, will not exceed the maximum allowable value.

4. APU Control

The Power Split block, see Figure (1), will assign a certain power value to the APU at every sample. This power assignment is represented by a desired torque/speed pair. Thus, control of engine speed and torque is needed to guarantee that the engine will operate at the desired points. Two subcontrollers are employed for this purpose. One PI controller is being used to control the output torque of the engine through manipulating the throttle angle. Another PI controller is used to control the speed of the engine by manipulating the generator output torque.

5. Simulation Results

The Power Split as well as the Thermostat strategies are tested by simulation. For this purpose, a detailed simulation software is being used. Standard urban and highway schedules (FUDS: Federal Urban Driving Schedule and FHDS: Federal Highway Driving Schedule) are used to evaluate the fuel economy of the vehicle under these schedules.

The vehicle under consideration has a total mass of 1628 Kg and is powered by a 40 KW APU (40 KW Diesel engine and a 40 KW generator) and a 60 KW Lead-Acid battery. The prime mover is a 70 KW AC Induction motor.

The results of fuel economy simulations are shown in Table (1). The table shows the fuel economy values for both strategies in urban and highway driving. Other results are shown in Tables (2) and (3); these are the energy flow (in and out) of the engine and the battery,

* A Thermostat is working in the background

* If the lower SOC value is reached , then,:

- APU is on
- Papu=maximum(Popt,Pcm)
- Papu =< Pmax
- Pbatt=Pcm-Papu

* If the higher SOC value is reached, then:

- APU is idle if (Pcm < = Pmin)
  # Papu=0
  # Pbatt=Pcm
- APU is on if (Pmin < Pcm < Pmax)
  # Papu=Pcm
  # Pbatt=0
- APU is on if (Pcm >= Pmax)
  # Papu=Pmax
  # Pbatt=Pcm-Papu

* In any case:

- If Acm > 3.5 m/s^2 then Papu=P_max_rated
- If Pcm < 0 then Regenerative Braking is active provided:
  # V > 5mph

* P_batt_ch <= P_batt_ch_max
* P_batt_disch <= P_batt_disch_max

Figure 2: The rules used in the Power Split Strategy

and the average efficiencies of these units.

Figure(3) shows the desired speed (a single FHDS cycle) as well as the actual vehicle speed under the Power Split strategy. The error in speed tracking is about ± 1 mph (mile per hour). The speed tracking under the Thermostat is similar.

Table 1: Fuel Consumption in mpg (mile per gallon)

Cycle	Power Split	Thermostat
Urban	46.5	41.7
Highway	70.6	66.4

The commanded and actual vehicle accelerations throughout a single FHDS schedule under the Power Split strategy are shown in Figure (4). The RMS (root mean square) of the error is 0.3 $\frac{m}{s^2}$. This acceleration tracking, though not perfect, is acceptable since it was enough to command the power sources to drive the vehicle over the driving schedules successfully.

Table 2: Energy In/Out and Efficiencies During the Urban Cycle (Energy Units in MJ)

	Power Split	Thermostat
Engine Energy in	75.1	78.8
Engine Energy out	29.3	30.5
Engine Efficiency	39%	39%
Battery Energy in	11.7	18.9
Battery Energy out	7.0	13.1
Charge Efficiency	91%	91%
Discharge Efficiency	96%	86%

Table 3: Energy In/Out and Efficiencies During the Highway Cycle (Energy Units in MJ)

	Power Split	Thermostat
Engine Energy in	108.5	109.2
Engine Energy out	42.1	42.6
Engine Efficiency	39%	39%
Battery Energy in	11.1	17.7
Battery Energy out	6.7	12.9
Charge Efficiency	93%	93%
Discharge Efficiency	95%	85%

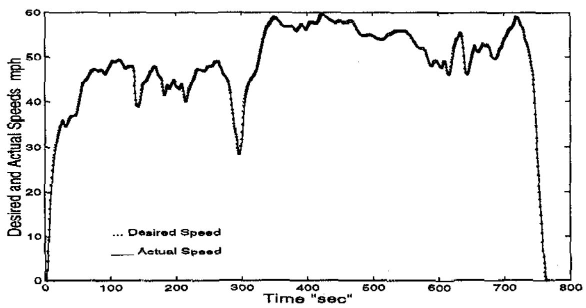

Figure 3: Desired and Actual Vehicle Speeds Under Power Split and a Single FHDS Cycle

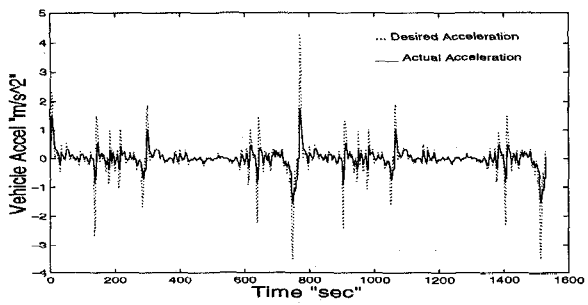

Figure 4: Desired and Actual Vehicle Accelerations Under Power Split and Two FHDS Cycles

Figure (5) shows more details of how the Power Split works. Three variables are shown in the figure: the power demand, the APU output power and the battery power. A positive battery power means the battery is discharging. The behavior of these variables under the Thermostat strategy are shown in Figure(6). A difference in behavior between the two strategies can be seen in these figures. Under the Thermostat, the APU power is either on or off. However, under the Power Split strategy as seen in Figure(5), the APU power can come up at any time whenever the power demand exceeds the threshold (P_{min}).

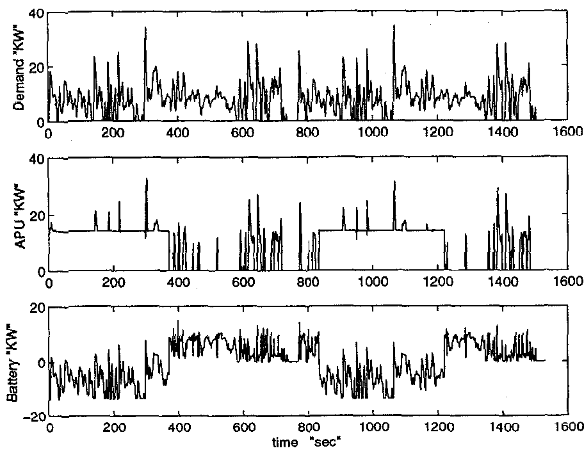

Figure 5: Power Demand, APU and Battery Powers Under Power Split and Two FHDS Cycles

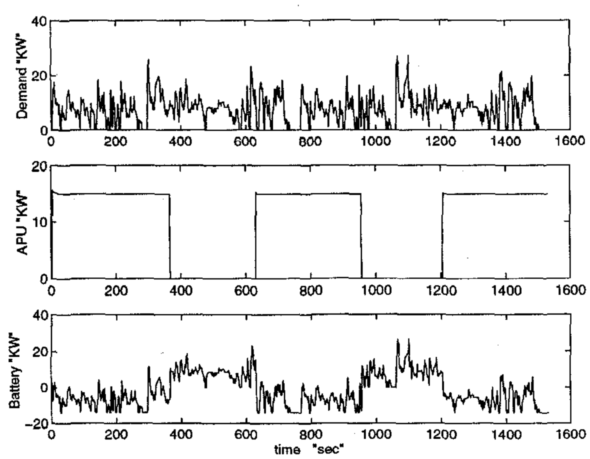

Figure 6: Power Demand, APU and Battery Powers Under Thermostat and Two FHDS Cycles

The state of charge of the battery under three FUDS cycles is shown in Figure(7) for the Power Split and in Figure (8) for the Thermostat. It is apparent that under the Power Split, the battery cycling is slower than that of the Thermostat.

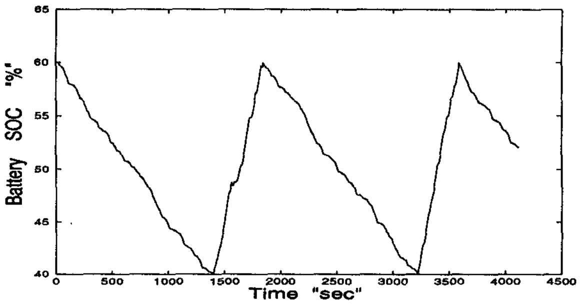

Figure 7: Battery SOC Under Power Split During Three FUDS Cycles

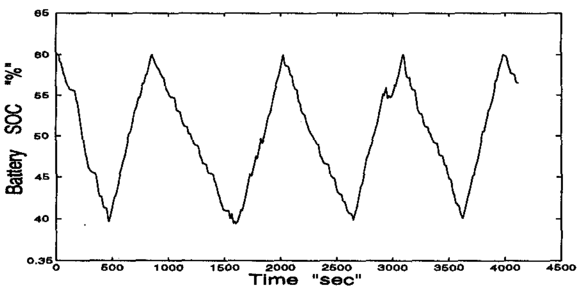

Figure 8: Battery SOC Under Thermostat During Three FUDS Cycles

6. Discussion and Conclusions

The main idea in implementing the Power Split strategy is to use the engine whenever it is possible provided that it will operate efficiently. Thus, the energy delivered by the battery will be reduced. This was the main reason for improving the fuel economy under the Power Split strategy compared to that of the Thermostat. This can be seen in Tables (2) and (3). In both tables, the discharge efficiency of the Power Split is higher than those of the Thermostat. The charge efficiencies under both strategies are the same since identical logic has been used for charging the battery.

Acceleration control was considered in this research in order to improve the vehicle response to driver's demand to follow the speed schedule. Imperfect acceleration tracking is the result of using a linear PI controller to control a nonlinear system. A more sophisticated control design method is needed to obtain better tracking.

In this research, the sizes of the APU and the battery are fixed to certain values. However, the performance of the energy management strategies is sensitive to the choice of the sizes of the power sources [3] . This issue is dealt with in reference [6].

7. Acknowledgements

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8. Nomenclature

A	:	actual vehicle acceleration
A_{cm}	:	desired vehicle acceleration
D_{cm}	:	driver command
P_{cm}	:	power command (demand)
P_{batt}	:	battery power
$P_{batt-ch}$	:	battery charging power
$P_{batt-disch}$	:	battery discharge power
$P_{batt-ch-max}$	:	battery maximum charging power
$P_{batt-disch-max}$	:	battery maximum discharging power
P_{apu}	:	APU output power
P_{min}	:	minimum engine power in high efficiency region
P_{max}	:	maximum engine power in high efficiency region
P_{opt}	:	optimum engine power
V	:	actual vehicle speed

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