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Optimal Energy Management Strategy for Parallel Hybrid Electric Vehicles

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Abstract

This paper presents an energy management strategy based on the multilevel hierarchical control for the parallel Hybrid Electric Vehicles (HEVs). The simulation model of this energy management strategy is constructed by using Matlab/Simulink/Stateflow and is optimized by applying the genetic algorithm. Under the satisfaction with the vehicle dynamic property and the balance of the state of charge of the battery, this energy management strategy properly determines the direction and quantity of the energy flow in the power train of the parallel HEV and makes the engine, the motor, the ISG and the battery operate efficiently in optimal state in order to minimize the fuel consumption and emissions.

Keywords: Parallel HEVs, Power Train, Hybrid Strategy, Energy Efficiency, Simulation

1 Introduction

The energy management strategy for the Parallel Hybrid Electric Vehicle (PHEV) is a key technology influencing the PHEV performance. This paper presents an energy management strategy for the PHEV based on the multilevel hierarchical control and the genetic algorithm optimization. According to the driver demand and the operating state of the power train components, this energy management strategy properly determines the energy distribution modes, the energy flow paths and their energy quantities, and optimally assigns the torque required by the power train between the engine and the motor/ISG in order to improve the vehicle comprehensive performance, such as the maximum dynamic property, the minimum fuel consumption and emissions. The structure of PHEV researched in this paper is shown in Figure 1. In this PHEV, the engine torque and the motor torque are coupled before the transmission and the Integrated Starter Generator (ISG) is used.

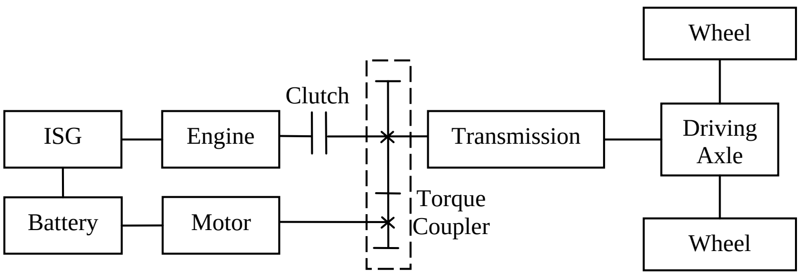

Figure 1: Structure of PHEV

2 Energy management strategy based on multilevel hierarchical control for PHEV

The multilevel hierarchical control system [1] of the PHEV power train is shown in Figure 2 and is divided into the following three levels from high to low according to the function.

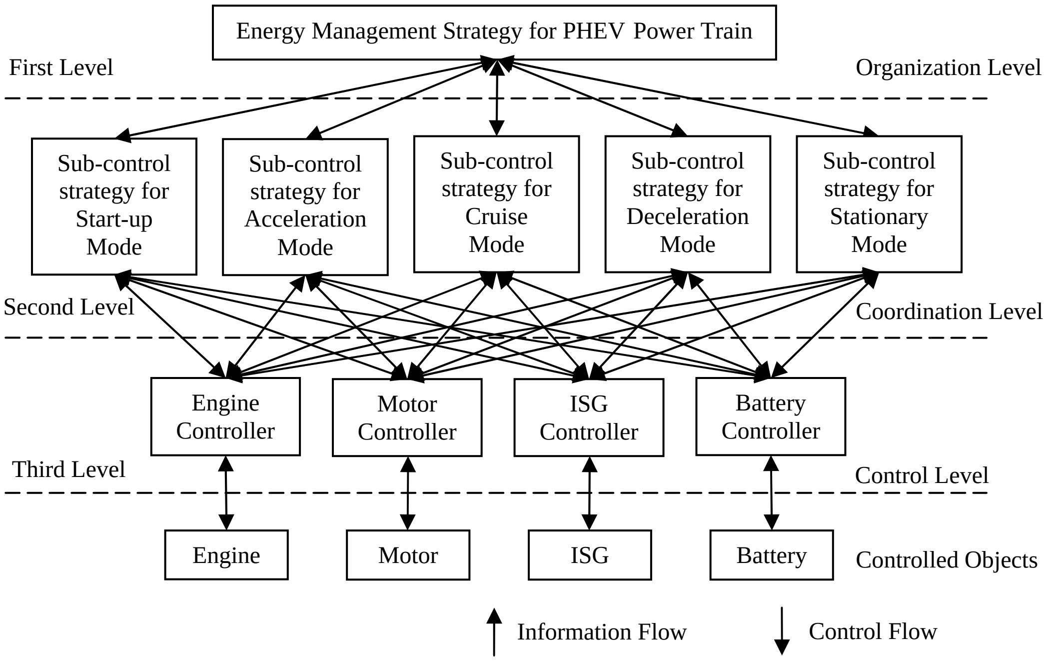

Figure 2: Structure of multilevel hierarchical control system of PHEV power train

(1) Organization level
The energy management strategy for the PHEV power train belongs to the organization level. This level has the ability of decision, judges the vehicle operating mode (start-up, acceleration, cruise, deceleration or stationary) in accordance with the vehicle operating information, and then selects the corresponding sub-control strategy in the second level.

(2) Coordination level
All sub-control strategies for different operating modes belong to the coordination level. This level coordinates the control role of the engine controller, the motor controller, the ISG controller and the battery controller, and resolves the conflict among them. Sub-control strategies for different operating modes properly determine the operating parameters of the engine, the motor, the ISG and the battery in terms of the vehicle speed and torque required by the driver.

(3) Control level
The engine controller, the motor controller, the ISG controller and the battery controller belong to the control level. This level directly gives the instructions to the engine, the motor, the ISG and the battery, and controls their operations.

In comprehensive consideration of the vehicle dynamic property, the balance of the State Of Charge (SOC) of the battery and other demands, the operating states of the engine, the motor and the ISG of the PHEV under all kinds of operating mode are determined in Table 1. Table 1 also indicates the directions of the energy flow in the PHEV under all kinds of operating mode. The motor assists the engine to drive the vehicle in the acceleration mode and performs regenerative braking to brake the vehicle in the deceleration mode. The ISG starts the engine when the engine needs to be started, and absorbs the redundant engine output and operates as the generator to charge the battery in the cruise mode. In deceleration mode, if the vehicle can brake safely and the battery is allowed to be charged, the regenerative braking will be used as much as possible and most of the kinetic energy of the decelerating vehicle can be retrieved to charge the battery.

Table 1: Operating states of engine, motor and ISG

Vehicle Operating Mode / Engine, Motor, ISG / Battery SOC	Start-up (V≤ Vstart)	Acceleration (V>Vstart)	Cruise	Deceleration	Stationary
0%-50%	M00 ISG01 Eon	M00 ISG00 Eon	M00 ISG10 Eon	M11 ISG00 Eoff	M00 ISG00 Eoff
50%-70%	M01 ISG00 Eoff	M01 ISG00 Eon	ISG10/M01 Eon	M11 ISG00 Eoff	M00 ISG00 Eoff
70%-100%	M01 ISG00 Eoff	M01 ISG00 Eon/Eoff	M01 ISG00 Eon/Eoff	$SOC \geq SOC_{max}$? Yes: M00 ISG00 Eoff No: M11 ISG00 Eoff	M00 ISG00 Eoff

E- Engine, Eon- Engine is on, Eoff- Engine is off
M- Motor, M00- Motor idles, M01- Motor propels, M11- Motor performs regenerative braking
ISG00- ISG idles, ISG01- ISG starts engine, ISG10- ISG generates electricity
V-Vehicle speed, V_{start}- Beyond this vehicle speed the start-up mode terminates
SOC_{max}- Beyond this maximum SOC the battery is forbidden to be charged

3 Optimization of energy management strategy for PHEV

3.1 Optimization problem

The distribution of the torque required by the power train between the engine and the motor/the ISG should be optimized, and then the quantities of the energy flow in different directions in the PHEV under different operating modes will be determined. This optimization problem is identified with the following constrained optimization problem.

$$\min J = k_1 \cdot \frac{x_{fuel}}{x_{fuel,aim}} + k_2 \cdot \frac{x_{Nox}}{x_{Nox,aim}} + k_3 \cdot \frac{x_{CO}}{x_{CO,aim}} + k_4 \cdot \frac{x_{HC}}{x_{HC,aim}} + k_5 \cdot \frac{x_{PM}}{x_{PM,aim}} \tag{1}$$

$$s.t. \quad \max(|\Delta V_{veh}|) \leq \delta_1 \tag{2}$$

$$|\Delta SOC| \leq \delta_2 \tag{3}$$

In Equation (1)~(3), J is the objective function in comprehensive consideration of the fuel consumption and emissions [2]; k_1~ k_5 respectively are the weights of the fuel consumption and all kinds of emissions, k_1~ $k_5 \in [0, 1]$; x_{fuel} is the fuel consumption (L/100km); x_{Nox}, x_{CO}, x_{HC} and x_{PM} respectively are the actual emissions (g/100km)of Nox, CO, HC and PM; $x_{Nox,aim}$, $x_{CO,aim}$, $x_{HC,aim}$ and $x_{PM,aim}$ respectively are the aim emissions (g/100km) of Nox, CO, HC and PM; $\frac{x_{fuel}}{x_{fuel,aim}}, \frac{x_{Nox}}{x_{Nox,aim}}, \frac{x_{CO}}{x_{CO,aim}}, \frac{x_{HC}}{x_{HC,aim}}$ and $\frac{x_{PM}}{x_{PM,aim}}$ are percentages and can be summed up with their weights; ΔV_{veh} is the difference between the requested and achieved vehicle speed during the driving cycle; δ_1 is the allowable deviation of the vehicle speed; ΔSOC is the difference between the initial SOC and the final SOC during the driving cycle; δ_2 is the allowable deviation of the SOC. The design variables are the engine torque, the motor torque and the ISG torque.

The first constrain condition Equation (2) is used to make the achieved vehicle speed attain the requested vehicle speed so that the PHEV can satisfy the dynamic demand. The second constrain condition Equation (3) aims at maintaining the balanced SOC.

3.2 Optimization algorithm

The energy management strategy for the PHEV is optimized by applying the genetic algorithm. The genetic algorithm is universal, efficient and robust, and it is a global optimization and parallel algorithm.

Genetic algorithms have been used to solve difficult problems with objective functions that do not possess properties such as continuity, differentiability, etc. Genetic algorithms maintain and manipulate a population of solutions and implement a "survival of the fittest" strategy in their search for better solutions. This provides an implicit as well as explicit parallelism that allows for the exploitation of several promising areas of the solution space at the same time. The implicit parallelism is due to the schema theory, while the explicit parallelism arises from the manipulation of a population of points– the evaluation of the fitness of these points is easy to accomplish in parallel.

Genetic algorithms search the solution space of a function through the use of simulated evolution, for example, the survival of the fittest strategy. In general, the fittest individuals of any population tend to reproduce and survive to the next generation, thus improving successive generations. However, inferior individuals can, by chance, survive and also reproduce. Genetic algorithms have been shown to solve linear and nonlinear problems by exploring all regions of the state space and exponentially exploiting promising areas through selection, crossover and mutation operations applied to individuals in the population.

The use of a genetic algorithm requires the determination of six fundamental issues: chromosome representation, selection function, genetic operators making up the reproduction function, the creation of the initial population, termination criteria and the evaluation function [3].

The genetic algorithm is used to maximize the evaluation function, but *J* needs to be minimized. Hence, the evaluation function is defined as -*J*. When using the genetic algorithm to optimize the energy management strategy, the Genetic Algorithms for Optimization Toolbox (GAOT) is applied [4].

3.3 Optimal engine operating curve

When the energy management strategy for the PHEV is optimized, the optimal engine operating curve and the low engine efficiency curve (shown in Figure 3) should be optimized in order to make the engine operate at its efficient region.

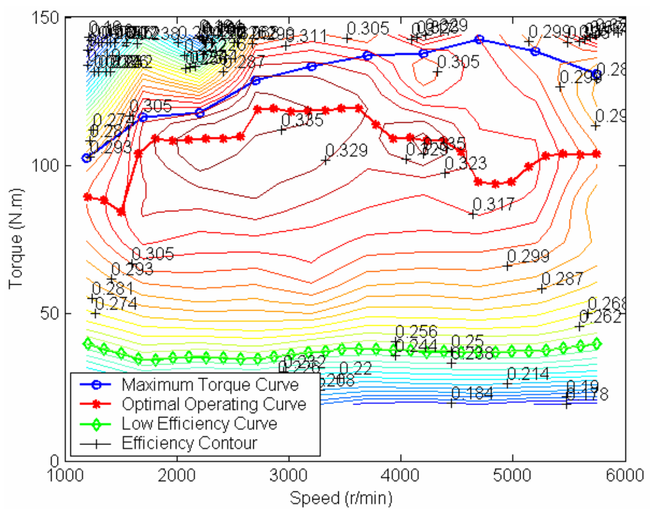

Figure 3: Engine operating curves

The optimal engine operating curve is the minimum engine fuel consumption curve which connects the minimum engine fuel consumption speed-torque operating points at different engine speeds. The low engine efficiency curve connects the allowable low engine efficiency speed-torque operating points at different engine speeds. The engine had better operate at the efficient region above this curve in the engine efficiency map.

4 Modeling and simulation of energy management strategy for PHEV

4.1 Modeling of energy management strategy

The model of the energy management strategy for the PHEV is constructed by using Matlab/Simulink/Stateflow. Stateflow is a powerful graphical design and development tool for complex control and supervisory logic problems. Stateflow provides clear, concise descriptions of complex system behavior using finite state machine theory, flow diagram notations, and state-transition diagrams. Stateflow brings system specification and design closer together. It is easy to create designs, consider various scenarios, and iterate until the Stateflow diagram models the desired behavior. Stateflow can take advantage of the integration with the MATLAB and Simulink environments to model, simulate, and analyze the energy management strategy for the PHEV.

4.2 Simulation of energy management strategy

The constructed model of the energy management strategy is integrated into the PHEV model and various comparative simulations under typical driving cycles are developed with the hybrid electric vehicle simulation tool HEVSim [5]. The characteristics of the PHEV used in the simulation are summarized in Table 2.

Table 2: PHEV characteristics

Parameter	Value
Gross Mass(kg)	1685
Coefficient of Rolling Resistance	0.009
Coefficient of Aerodynamic Drag	0.25
Frontal Area(m^2)	2.39
Engine Power(kW)	80
Motor Propelling Power(kW)	28
Motor Generating Power(kW)	20
ISG Propelling Power(kW)	3
ISG Generating Power(kW)	10
Battery Capacity(Ah)	8

The simulation results of this PHEV with the optimal multilevel hierarchical energy management strategy over one NEDC driving cycle are depicted in Figure 4. The Figure 4 shows the curves of vehicle speed, SOC, engine torque, motor torque and ISG torque. The curve of vehicle speed shows that the achieved vehicle speed is very close to the speed of the NEDC driving cycle so that the speed trace ability and the vehicle dynamic property are better. The curve of SOC shows that the final SOC is very close to the initial SOC. The curve of engine torque shows that when the PHEV starts, the engine is off so that the fuel consumption is reduced; when the PHEV cruises, the engine outputs constant torque at its efficient region according to the optimal engine operating curve. The curve of motor torque shows that when the PHEV starts, the motor provides the positive torque to solely start the PHEV; when the PHEV brakes, the motor provides the negative torque to perform regenerative braking. The curve of ISG torque shows that the ISG provides the positive required torque to start the engine and absorbs the negative redundant engine torque to generate electricity.

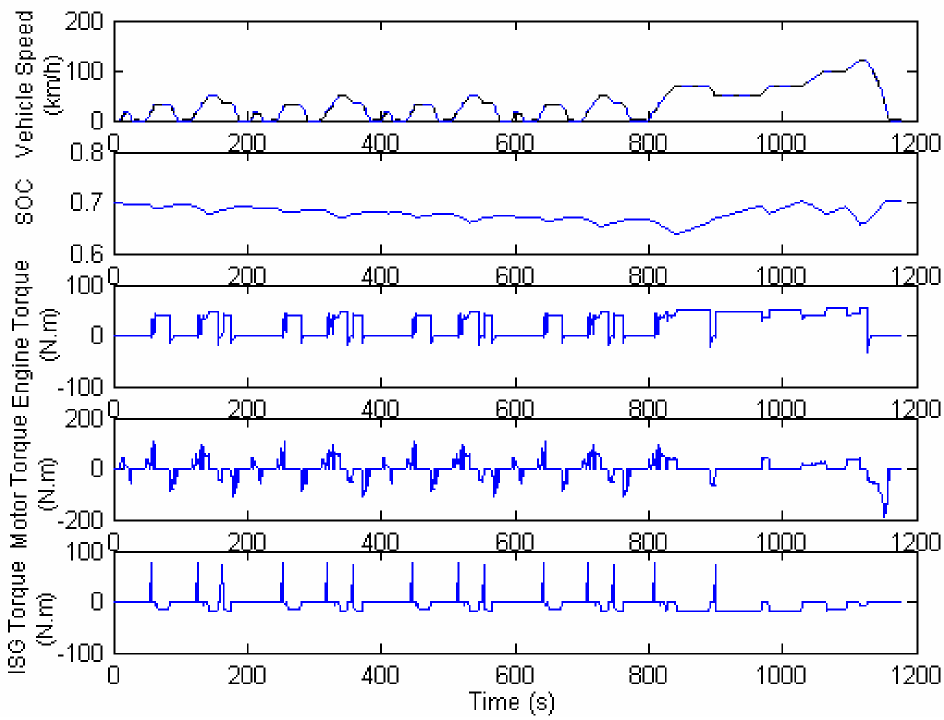

Figure 4: Simulation results

The fuel consumption and the final SOC of PHEV respectively with the optimal multilevel hierarchical energy management strategy and the PNGV System Analysis Toolkit (PSAT) built-in PHEV energy management strategy over one NEDC driving cycle are compared in Table 3. Because there are not emissions data for this engine, there are not the results of the emissions. The Table 3 demonstrates that the optimal multilevel hierarchical energy management strategy can better reduce the fuel consumption and maintain the balanced SOC when making the PHEV satisfy the dynamic demand.

Table 3: Comparison of different energy management strategies

Energy Management Strategy	Fuel Consumption (L/100km)	Final SOC (Initial SOC=0.7)
Optimal Multilevel Hierarchical Energy Management Strategy	6.0775	0.7029
PSAT Built-in Energy Management Strategy	7.1597	0.7557

5 Conclusion

Under the satisfaction with the vehicle dynamic property and the balance of the battery SOC, the optimal energy management strategy based on the multilevel hierarchical control and the genetic algorithm optimization can properly determine the direction and quantity of the energy flow in the PHEV and make the main power train components operate efficiently so that the fuel consumption and emissions can be reduced.

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