The Design of Control Strategy for Blended Series-Parallel Power-Split PHEV – a Simulation Study

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Abstract: - Electric Vehicles (EVs) have been extensively researched to reduce the fuel consumption and tailpipe emission. The series-parallel power-split Plug-in Electric Vehicle (PHEV) has been considered as one of the most suitable candidates. It contains both an internal combustion engine (ICE) and an electrical storage system (ESS) to achieve a better driving performance. The energy management system (EMS) is significant for a PHEV to improve the efficiency of the whole system. Electric vehicle mode (EV), charging depletion (CD) and charging sustaining (CS) modes will be discussed to build a control strategy in this study. This control strategy will be implemented with the state of charge (SoC) to show its impact through a simulation study.

KeyWords: - Blended mode; Control strategy; Emission; Fuel economy; PHEV; Simulation; SoC

1 Introduction

The issues on Global Warming resulted from burning of fossil fuel has been discussed for decades. The Electric Vehicle (EVs) as a potential candidate to reduce the air pollution from traffic section and to relieve the pressure from energy exhaustion have been researched extensively [1-3]. Based on the forms of energy transmission systems, the EVs could be categorized into three different types: Pure/Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV) and Hybrid Electric Vehicles (HEV) [4]. With the different control strategy and various selections of the components, the performance of EVs will be different, especially in terms of fuel consumption and tailpipe emission [5]. The Plug-in Hybrid Electric Vehicle (PHEV) take the advantage of hybrid energy resources promise to the future transport utilization. The optimal internal energy management of PHEV has been widely discussed[6].

In this paper, the series-parallel structures of the PHEVs will be briefly introduced firstly. Taking the advantages of blended mode in series-parallel power-split PHEV, an optimization design of internal energy management will be demonstrated next. The final part will focus on the simulation results and discussion and conclusions from this work.

2 Optimization Design for Series-parallel Power-split PHEV

The PHEV inherits the features of HEV that includes both Internal Combustion Engine (ICE) and Energy Storage System (ESS). Fig.1 shows the connecting status for PHEV [7]. The PHEV introduces the grid-able battery technology to extend the energy density in a euphemistical way [8]. The fundamental connecting modes between ICE and battery are similar with conventional HEV, while the grid-able battery changes the working principle.

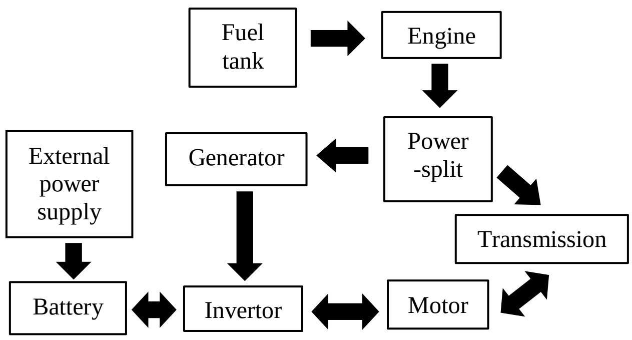


Fig.1 Series-parallel PHEV

2.1 Blended mode for the series-parallel power-split PHEV

For the series-parallel power-split PHEV, a complex system cannot be avoided. Since the grid-able battery has been introduced, the primary working principle of the PHEV differs from other types of EVs. The working state in PHEV includes three different types: (1) EV mode where the propulsion is solely provided by battery pack, (2) Charge Depletion (CD) mode where both battery and engine work in a parallel structure with the electricity as the main power, and (3) Charge Sustaining (CS) mode where the engine provides a considerable propulsion despite being the main provider [7]. In order to improve the efficiency and to achieve reduced fuel consumption and emission and to ensure a better vehicle performance at the same time, EMS seems important and EMS optimization has been extensively researched [9-13].

2.2 The EMS optimization models

EMS relies on several parameters. A critical parameter introduced to describe the instantaneous amount of electricity stored in the battery is the SoC. The EV and CD modes take priority in order to reduce the fuel consumption and emission as much as possible. The CS mode allows the ICE to recharge the battery when the SoC is lower. Otherwise, the ICE and battery work collectively when the power demand is high [11, 12].

2.2.1 Rule-based SoC control strategy design

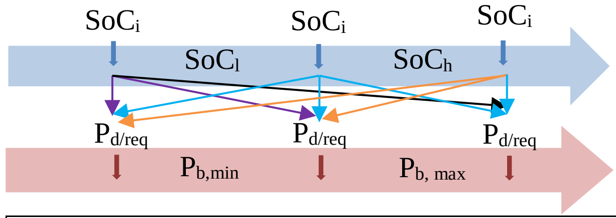
The design concepts for the strategy set the SoC as the priority and then consider the relationship between the power requirements and the maximum power of the battery. Another significant purpose is lasting the time of pure electric propulsion and charging depletion as long as possible. In other words, it increases the percentage of EV and CD mode in the total logic control.

Conditions	Output mode
$\begin{cases} \mathrm{SoC}_i > \mathrm{SoC}_h \\ \mathrm{P}_{\mathrm{d/req}} < P_{b,max} \end{cases}$	EV mode (battery working solely)
$\begin{cases} \mathrm{SoC}_i < \mathrm{SoC}_l \\ \mathrm{P}_{\mathrm{d/req}} < P_{b,max} \end{cases}$	$\mathrm{CS_b}$ mode (optimized output)
$\begin{cases} \mathrm{SoC}_i < \mathrm{SoC}_l \\ \mathrm{P}_{\mathrm{d/req}} > P_{b,max} \end{cases}$	$\mathrm{CS_{eng2b}}$ mode (battery protection)
Other	CD mode (both ICE and battery working)

Fig.3 Functional relationships for offline CD mode optimization

Table 1 Parameters of SoC control strategy

Power demand/require	$\mathrm{P_{d/req}}$
Power from engine	$\mathrm{P_{eng}}$
High and low point SoC	$\mathrm{SoC_h}$, $\mathrm{SoC_l}$
Power from engine to charge battery	$\mathrm{P_{eng2b}}$
Instantaneous SoC (power stored in battery)	$\mathrm{SoC_i}$ ($\mathrm{P_{b,i}}$)
Maximum and minimum rated power of battery	$\mathrm{P_{b,max}}$, $\mathrm{P_{b,min}}$



→	EV mode Battery fully provides power for the vehicle; ICE is not working. $\mathrm{P_{eng}}=0$ ($\mathrm{P_{d/req}}=\mathrm{P_{soci}}$)
→	CD mode Battery fully provides power; ICE only provides the left to achieve the power demand. $\mathrm{P_{eng}}= \mathrm{P_{d/req}} - \mathrm{P_{b,max}}$
→	$\mathrm{CS_b}$ mode Battery fully provides main power for the vehicle; ICE charging the battery until achieves the point of $\mathrm{SoC_l}$. $\mathrm{P_{eng}}=(\mathrm{P_{d/req}}-\mathrm{P_{b,i}})+(\mathrm{P_{b,i}}-\mathrm{P_{SoCl}})$
→	$\mathrm{CS_{eng2b}}$ mode ICE provides main power for vehicle preferentially, then charging the battery till it is reaching the $\mathrm{SoC_l}$. $\mathrm{P_{eng}}-\mathrm{P_{d/req}}=\mathrm{P_{eng2b}}$ ($\mathrm{P_{eng2c}} \leq \mathrm{SoC_l}$)

Fig.2 Design logic of SoC control strategy

Fig.2 illustrates the design of SoC control strategy while the parameters used have been listed in Table 1. Based on the SoC strategy, Fig.3 shows the functional relationships between CD/CS mode and the strategical conditions.

3 Simulation Study

The initial simulation model is based on the ADVISOR (Advanced Vehicle SimulatOR) in MATLAB/Simulink operating environment. The strategy of SoC model will be set in MATLAB/Simulink with Simdriveline models which will invoke the same structural parameters from models of ADVISOR operated in the initial simulation. The significant part of SoC strategy control will be built in Simulink Stateflow to optimize the powertrain control for the whole hybrid system.

3.1 The model setting

The initial simulation model setting adopts the models of the first generation Toyota Prius in ADVISOR. The significant parameters for the operation window set in initial ADVISOR model are listed in Table 2. The crucial model of SoC strategy control logic state designed in the second part has been built in Simulink Stateflow logic chart, in which the critical value of SoC_h and SoC_l are set to 0.80 and 0.30, respectively.

Table 2 Parameters of ADVISOR model setting in simulation

Engine	Motor: 1.5 L Straight-4|I4 DOHC 16 valve; 43 kW (58 hp) at 4000 rpm
	Torque: 102 N·m (75 lbf·ft) at 4000 rpm
Electric	Motor: 288 V 30 kW; 31 kW (40 hp) at 940-2000 rpm
	Torque: 305 N·m (225 lbf·ft) at 0-940 rpm
Energy Storage	NiMH battery with maximum 40 kW power
Transmission	Planetary gear continuously variable transmission model
Wheel/Axle	the constant coefficient of rolling resistance model
Accessory	constant power accessory load models
Override mass	1368 kg

3.2 Simulation and discussion

The parameters of initial conditions included several characteristics that can be adjusted from model blocks. For example, the value of the coefficient of air resistance is 0.3, wheel radius is 0.287m, wind award area is 1.746m^2 and the initial SoC_0 is 0.75. The input drive cycle adopted the Extra Urban Driving Cycle from a database of Economic Commission for Europe (CYC_ECE_EUDC) shown in Fig.5.

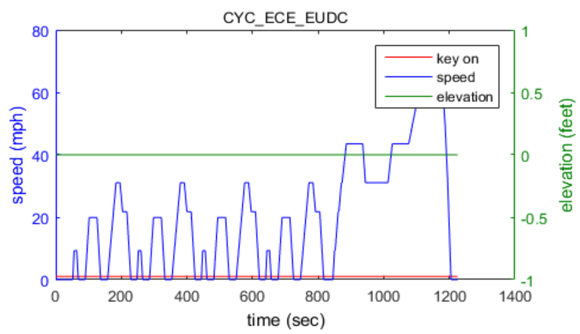
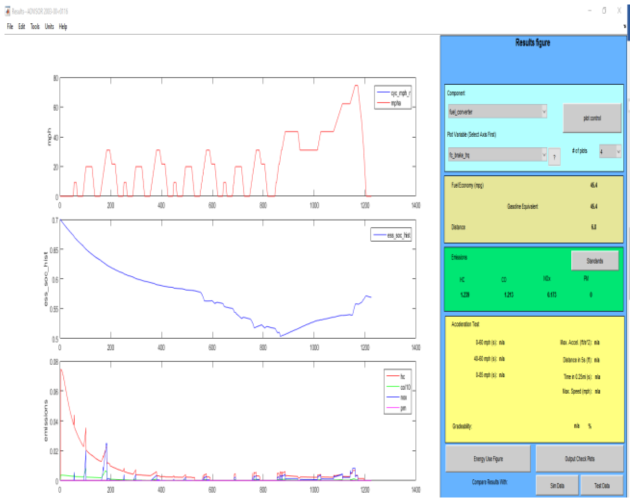
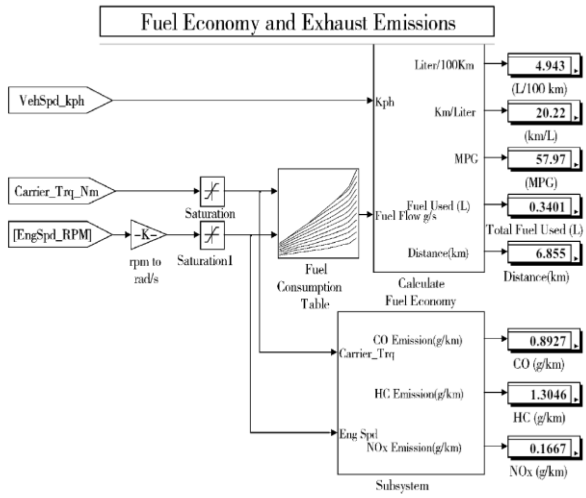


Fig.5 The speed input of CYC_ECE_EUDC

With the input of CYC_ECE_EUDC, the simulation was conducted the initial Prius model in ADVISOR running in MATLB/Simulink environment, while the SoC control strategy set in Stateflow invoked same parameters with initial model. The simulation results orderly showed in Fig.6 and Table 3 compares the specific output values from different emission characteristics. The emission of CO considerably reduced by 26.4% and the NO_x reduced by 3.6%. There is, however, an increase in HC by 5.3%.



(a) Initial model in ADVISOR



(b) SoC strategy design build by Stateflow in MATLAB/Simulink

Fig.6 The simulation results

Moreover, the simulation results showed that fuel economy (mpg) increased from 45.4 to 57.9 under the SoC control strategy. In terms of logic design, the engine works as the main power provider only in CSeng2b mode. In CD or CSb mode, the engine works as a parallel or auxiliary part to provide little propulsion. In other words, the vehicle performance has been improved considerably through the SoC control strategy.

Table 3 Comparison of Simulation results between ADVISOR and SOC strategy control models

Emission (g/km)	SoC strategy control model	Prius in ADVISOR model	Result
CO	0.8927	1.213	SOC-Decrease 26.4%
HC	1.3046	1.239	SOC-Increase 5.3%
NOx	0.1667	0.173	SOC-Decrease 3.6%

4 Conclusion

In this paper, a novel SoC control strategy has been designed. Combining the features of series-parallel power-split PHEV, two different working modes between engine and battery have been redefined as CS_b and CS_{eng2b}, which improve the possibility of CD mode and protect the battery. Compared to the original simulation of the ADVISOR model from 1st generation Toyota Prius, the SoC control strategy model successfully reduced the fuel consumption and emission. In terms of whole EMS design, other optimization on specific mode such as MPC (model predictive control) or DP (dynamic programming) and neural network optimization *etc.* [9-11, 13, 14], could be developed in the future to achieve better efficiency and performance as well.

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