Optimization of the Control Strategy for a 4-Wheel-Drive PHEV

Li-jun Qian
Hefei University of Technology，
Hefei，Anhui，China
hfutqlj@163.com

Li-hong Qiu
Hefei University of Technology，
Hefei，Anhui，China
qiulihong99@163.com

***Abstract*—In this paper, control strategy of a plug-in 4 wheel drive car is researched. According to torque request, SOC and velocity of the car, the steady work state is classified into 10 modes, which consists of 7 drive modes and 3 brake modes. The control strategy based on logic threshold realizes basic energy management of the car. Besides, the control strategy is optimized with the algorithm of NSGA-II, and fuel consumption and emissions are reduced without much decrease in the power performances.**

Keywords- PHEV; control strategy; simulation; optimization; NSGA-II;

I. INTRODUCTION

Compared with traditional 4 wheel drive car, plug-in hybrid electric car not only has the advantages of good controllability, passability and stability, it can be also used as pure electric vehicle under suitable conditions. With an all electric range of more than 70km, the plug-in 4WD hybrid car researched in this paper can cover the trip distance request of most people in a day. Therefore, it can reduce fuel consumptions and exhaust gas emissions. The plug-in HEV enjoys the advantages of pure electric vehicle, series HEV and parallel HEV. What's more, the power performances and drive range is nearly the same as traditional car. Therefore, there is an overwhelming trend that the plug-in HEV, especially the 4WD ones, will be increasingly popular in the market while energy reservation and emission reduction are widely advocated [1].

The plug-in 4WD hybrid car discussed in this paper has multiple drive modes. In the paper, working modes of this car under different conditions and the jump conditions among different modes are analyzed and a control strategy based on logical threshold is presented. In addition, NSGA-II is used to optimize the fuel consumption of the car and the iterative process of the variables and fuel consumption are showed in the figures and the performances before and after optimization are listed in the table.

II. BASIC STRUCTURE OF THE PHEV

The basic structure of the plug- in HEV is shown in Fig.1.

The power system consists of a generator, an ISG motor, a rear motor, a power cell, a CVT transmission and controllers of power components and the vehicle control unit. The ISG motor is arranged coaxially with the engine. The output shaft of the ISG motor is connected with the CVT to propel the front axle. The rear motor is connected to the real axle to propel the rear wheels. The power cell is connected to two inverters to transform the direct current of the battery to alternating current for the two motors. The DC-DC is used to provide low voltage electric for the electric accessories. The charger is used to recharge the power cell by using external power source. The power system of the car is coordinated by the vehicle control unit and controllers of power components. The basic parameters of the car are listed in table 1.

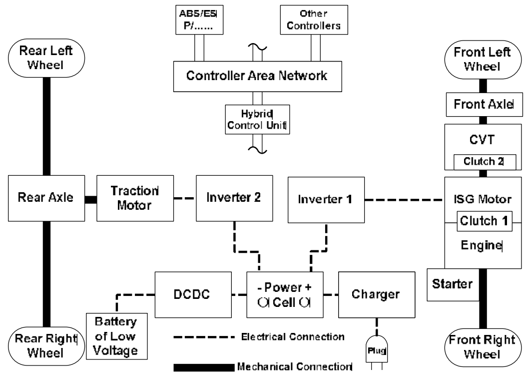


Fig.1 Structure of the plug-in 4WD HEV

Table1. Basic parameters of the car

Mass(kg)	1547
Coefficient of air resistance	0.35
Frontal area(㎡)	2.2
Rolling radius of wheel(mm)	289
Coefficient of rolling resistance	0.014
CVT transmission ratio range	0.412-2.932
Ratio of front final drive	5.297
Ratio of rear final drive	7.882
Engine maximum power (kw)	81
Engine maximum torque (N·m)	150
Rated and maximum power of ISG motor (kw)	18/30
Maximum torque of ISG (N·m)	100
Rated and maximum power of rear drive motor(kw)	20/35
Maximum torque of rear drive motor(N·m)	120
Capacity of battery pack(A·h)	40

III. BASIC ENERGY MANAGEMENT STRATEGY

The basic control strategy is as follows:

1) When the car starts to move, its velocity is very low, the torque request is within the torque range of the rear motor at its current speed. If the state of charge (SOC) of the power cell is higher than low limit value of its best work area, only the rear motor is used to drive the car, taking full advantage of the feature that the output torque of the rear motor is constant at low speed. It's EV mode at this time.

2) If the torque required by the car is lower

than the maximum torque that can be provided by the rear motor at its current speed and the SOC of battery is in the low SOC area, the engine will drive the ISG motor to provide power for the battery, At this time, the rear motor drives the car, and it is the series mode.

3) If the torque required by the car is higher than the maximum torque provided by the rear motor but lower than maximum engine torque at its current speed and the SOC of the battery is in the normal area, the car will be driven by the engine alone. It's engine mode.

4) If the SOC of the battery is in the low SOC area, and the torque required is higher than the maximum torque that the rear motor is able to provide at the current speed, the engine will work at the best fuel economic area and the spare torque will be used to drive the ISG motor which is used as a generator to charge the battery. It's engine drive and generate mode.

5) If the required torque is higher than the upper limit of the engine at its current speed, and lower than the sum of the maximum torque that can be provided by the engine and ISG motor, and SOC of the battery is high. Then the engine and ISG motor provide the torque required cooperatively. It is ISG aided parallel mode.

6) If the torque required is higher than the sum of upper limit of the engine and ISG motor, lower than the sum of the maximum torque that can be provided by the engine and the rear motor, and SOC of the battery is high. Then rear motor works together with the engine to provide the auxiliary torque for the car. It is rear motor aided 4WD mode at this time.

7) If the required torque is higher than the sum of the maximum that can be provided by either the engine and the rear motor or the engine and the ISG motor at their current speeds, and the velocity is within the limit of the rear motor, the car will work at the all hybrid 4WD mode, in which all the power components work together to provide the required torque of the car.

What's more, when torque request is lower than zero the car goes into brake mode, In accordance with the difference among different brake intensities, the brake mode can be classified into regenerative brake mode, blend brake mode and mechanical brake mode [2-6]. During regenerative brake mode and blend brake mode, ISG motor and rear motor are used as generators to recharge the battery.

According to the energy management rules mentioned above, the stateflow diagram of the 4WD car is modeled in matlab/simulink/stateflow, and the model is shown in Fig.2 And CRUISE is used for the simulation of the control strategy. The simulation cycle is NEDC and initial SOC of the battery is 90%. Work points of the power components are show in Fig.3. At the beginning of the acceleration period, torque range of the rear motor can meet the need of drive torque of the car. So, the car is mainly driven by the rear motor. As car velocity arises to a certain value, the rear motor can't meet the torque request within its torque range. The car is driven either at engine mode or ISG aided parallel mode. When it is regenerative mode, the two motors work as generators to recycle the braking energy and their output torque is negative. From the work points of the power components, a conclusion is easily made that they just work as the control strategy indicates, so the control strategy is feasible

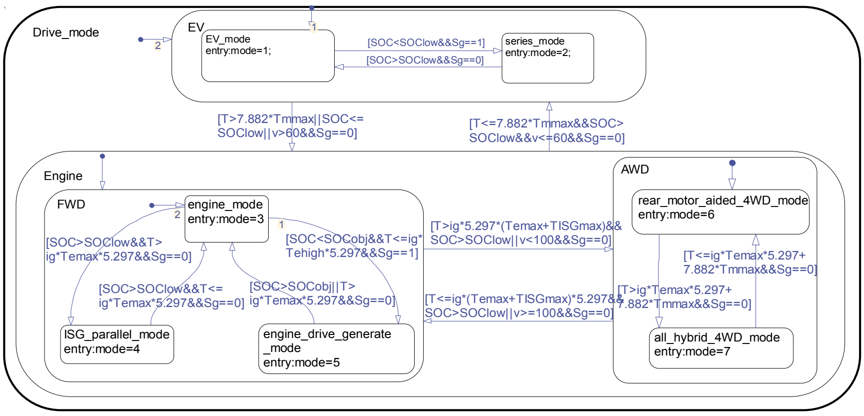
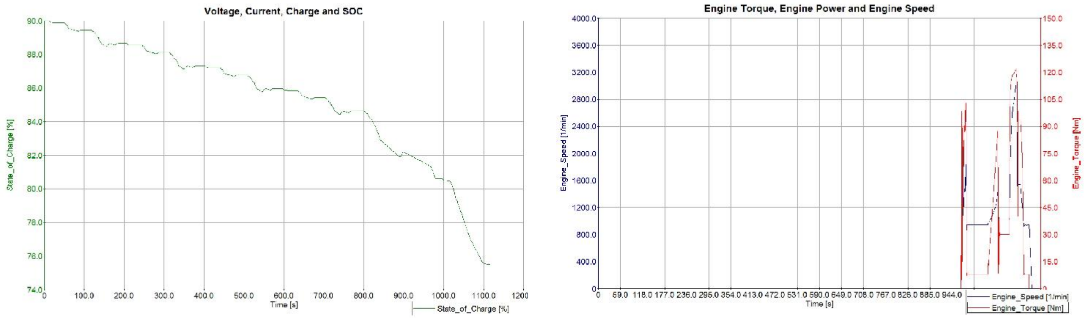
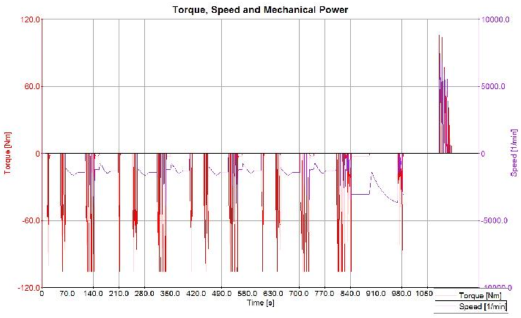


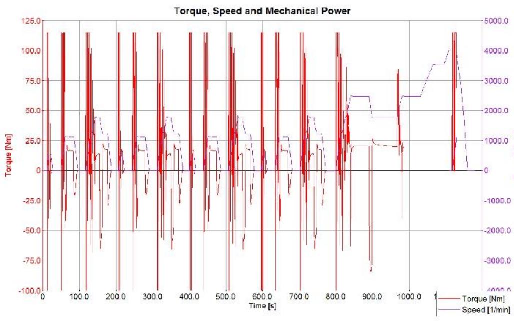
Fig.2 Stateflow diagram of drive mode



（a）SOC curve (b)Work point of the engine



(c)Work points of ISG motor



(d)Work points of rear motor

Fig.3 Work points of power components

IV. OPTIMIZATION OF THE CONTROL STRATEGY

Control strategy based on logic threshold is simple and widely used, but the control rules is based on the engineers' experiences which may not guarantee an optimal solution. So, it is essential to optimize the control strategy [7]. In order to avoid complicated programming in matlab. Isight software which is widely used is used to optimize the control strategy of the car. And the NSGA-II which is a multiple objective optimization algorithm is chosen. The model created in Isight is showed in Fig.4.

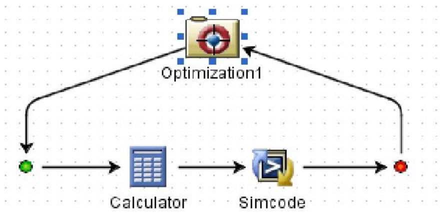
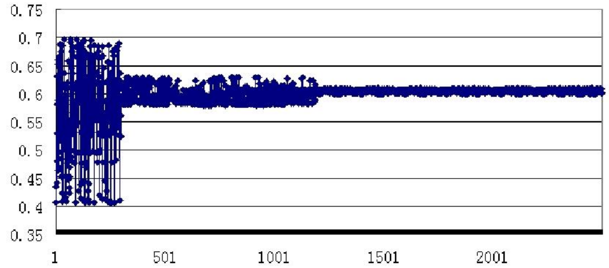


Fig.4 Isight model

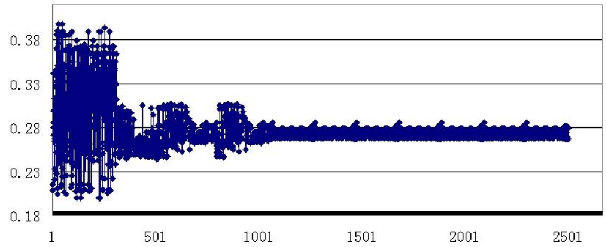
The simcode module has an input button, a command button, and an output button. The input reads the PHEV.dbf file which is in the directory of the PHEV model created in CRUISE. The command is a batch file which is written in DOS to recall the CRUISENT.exe to simulate the car model in the background. And the output transmits the simulation results to the results. log which is in the messages folder in the PHEV model's directory. The optimization module reads the results from the output of the simcode and optimizes the data with its algorithm which can be chosen by users and then transits the optimized data to the simcode. And the calculator module is used to set the constraints. After a certain times of circulation or the results meet user's demands, the optimization stops, and the objective functions and variables converges to a certain value or a small range.

Plug-in four wheel drive car has many parameters and it is not easy to optimize all of them. In this paper, five parameters which have significant effects on the performances of the car are chosen to be optimized. They are the i_f, i_r, v_0, SOC_{obj} and SOC_{low}. i_f and i_r stands for the transmission ratio of the final drive of the front and rear axle. v0 is the velocity which is one of the critical points that the drive mode of the car transfers between EV mode and hybrid mode. SOC_{obj} is the state of charge which is the critical point that the engine starts to recharge the battery with its extra torque, and SOC_{low} is the lowest limit that the battery can be used to drive the car without being recharged. The objective functions of the optimization are the fuel consumption, the acceleration time of 0-100km/h and the emissions which contains the NOx, CO, HC. The constraints includes the speeds and torque ranges of the power components and the range of the SOC of the battery and the transmission ratios of the final drive both in front and rear axle.

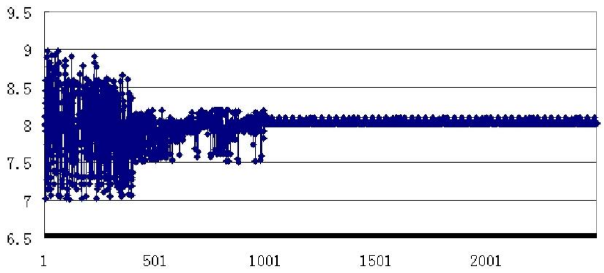
After a proper setting of the software, the optimization is executed. The iterative process of the variables and fuel consumption are shown in Fig.5. From the figure, a conclusion is made that all variables and objective functions converge to their certain values. And one of the Pareto optimal solutions is chosen to simulate the basic performances of the car and the results are shown in table.2. From table2, it is easy to arrive at a conclusion that the fuel consumption and emissions are reduced and the power performances of the car can meet the design index. So, the optimized solutions are feasible.



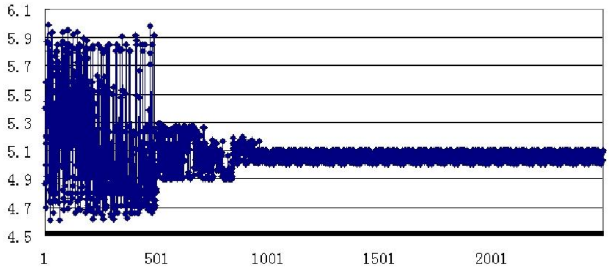
(a)Iterative process of SOCobj



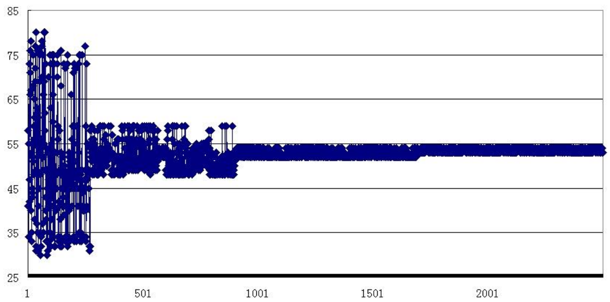
(b) Iterative process of SOC_{low}



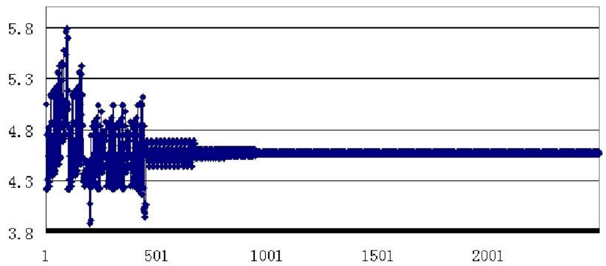
(c) Iterative process of rear final drive



(d) Iterative process of front final drive



(e) Iterative process of v_0



(f) Iterative process of fuel consumption

Fig.5 The iterative process of the variables and fuel consumption

Table2. Performances of the car

Items		**Design**	**Simulation results**	
			Original	*Final*
Maximum velocity(km/h)	EV	>100	103	101
	Hybrid	>170	178	181
0-100km/h acceleration time（s）		<10	8.7	8.9
Maximum inclination（%）		>50	54.6	51.7%
All electric range（NEDC）		>70	72.3	74.7
Fuel consumption (L/100km)		<5	4.87	4.61
i_f		--	5.297	5.089
i_r		--	7.882	8.034
v_0(km/h)		--	60	54
SOC_{obj}		--	0.55	0.605
SOC_{low}		--	0.3	0.273
Emission of NOx(g/km)		--	0.34	0.29
Emission of CO(g/km)		--	1.83	1.80
Emission of HC(g/km)		--	0.87	0.82

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