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Hybrid Electric SUV Based on Dual Rotor PM Motor

Du Yongchang[1], Yu Liangyao[1], Gao Jinwen[1], Song Jian[1]
[1.] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, No. 1 Qinghuayuan, Beijing 100084, China, duyc@tsinghua.edu.cn

Abstract

A hybrid electric SUV is developed. The characteristic of this hybrid SUV is utilizing a dual rotor PM motor system as the energy coupler and converter which replaces the generator and motor in a general HEV system, resulting in higher flexibility, efficiency and a compact size. The system configuration and control strategy for motor and engine in different operating modes are explained in detail. Finally, a simulation shows the advancement in fuel economy of this HEV compared with the original conventional SUV.

Keywords: HEV, motor, control strategy, power management, simulation, vehicle performance

1 Introduction

Nowadays Hybrid electric vehicle (HEV) is the most realistic solution to reduce fuel consumption and emission, for it reaches a compromise between performance and cost and technical realizability.

Different HEV configurations have their advantages and disadvantages. In a series HEV, the engine is totally mechanical independent of driving situations so that it allows the engine to always operate under optimal conditions. But all the power which the vehicle needs for driving suffers from the transformation from mechanical to electrical and electrical to mechanical. So the final fuel economy improvement is highly dependent to the efficiency of generator, motor and battery system. Another headache for series HEV system designers is it requires a full-sized generator and motor. In a parallel HEV, the engine and motor are both mechanically connected to driving shaft. So it can reduce the energy transformation lost and the generator/motor system can be smaller than those in a series HEV. But limitations exist in selecting engine working points because of its mechanical connection to the wheel.

The Department of Automotive Engineering and the Stake Key Laboratory of Automotive Safety and Energy at Tsinghua University have been working on various HEV projects for nearly two decades. This paper presents some efforts from a current on-going project support by the National High-tech R &D program (863 programs) of China, in which Beijing Automotive Group, Tsinghua University and Chinese Academy of Science are involved. In this project, a hybrid electric SUV is developed based on a dual rotor PM motor system which may be called electric variable transmission (EVT) somewhere. The dual rotor motor integrates the generator and motor in one. The engine can operate at an optimal working point independent to the vehicle speed and load. And through the internal power coupling mechanism, most of the power from engine can be transferred directly to the driving shaft, avoiding the transformation efficiency problem in a series HEV.

2 System Configuration

Fig. 1 shows the configuration of HEV system. The ICE engine is the power source to drive the vehicle. Its crankshaft is directly connected to the inner rotor of the motor system. The outer rotor is connected to a simple over-speed gearbox. The power output of the engine is coupled from inner rotor to outer rotor and drives the driving shaft. Extra power can be drawn from or delivered to the battery pack.

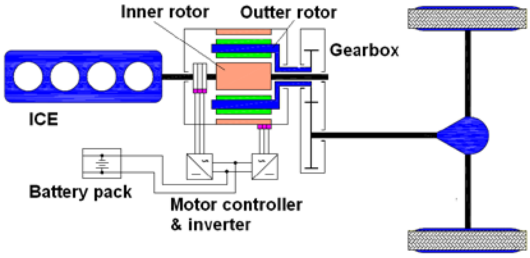

Figure 1: System Configuration

The system seems to be similar to a series HEV to some extent. The engine is mechanical disconnected with the driving shaft. Its speed and torque are highly independent to vehicle need, so it can always operate at an optimal point. But the advantages compare with series HEV are:

- the power coupling mechanism inside dual rotor motor allows most of the engine power to be transferred directly to outer rotor, avoiding the transform efficiency problem;
- the size of the dual rotor motor is smaller than the combination of full-sized generator and motor in series HEV.

The parameters of main components in HEV system is shown in table 1.

Table 1: Parameters

Engine		2.4Liter, 105kW, 217 N*m
Motor	Inner	38kW max., 150N*m max.
	Outer	200N*m(rating), 350N*m (max.)
Battery pack		Li-Ion, 360V, 7.5Ah * 2
Gearbox		1:1.2

3 Control Strategy

3.1 Basic Idea

The basic idea of control strategy is to control the engine to operate at its optimal operation point with best fuel economy and emissions. Its output is coupled either mechanically or electrically from inner rotor to outer rotor to drive the vehicle. In high load situation such as quick acceleration, motor system draw power from battery pack and serves as an auxiliary power source. When engine output is more than driving need, motor system transforms the power and charge the battery.

If the driving torque requirement is relatively small so that surplus power may exceed the battery's max charging limit if the engine still works in high efficiency point, the engine will be switch off. Battery/motor system becomes the only power source to drive the vehicle.

3.2 Engine

Fig. 2 shows the engine's efficiency map. From the point of view of maximizing engine efficiency, the engine should be controlled within the slash area.

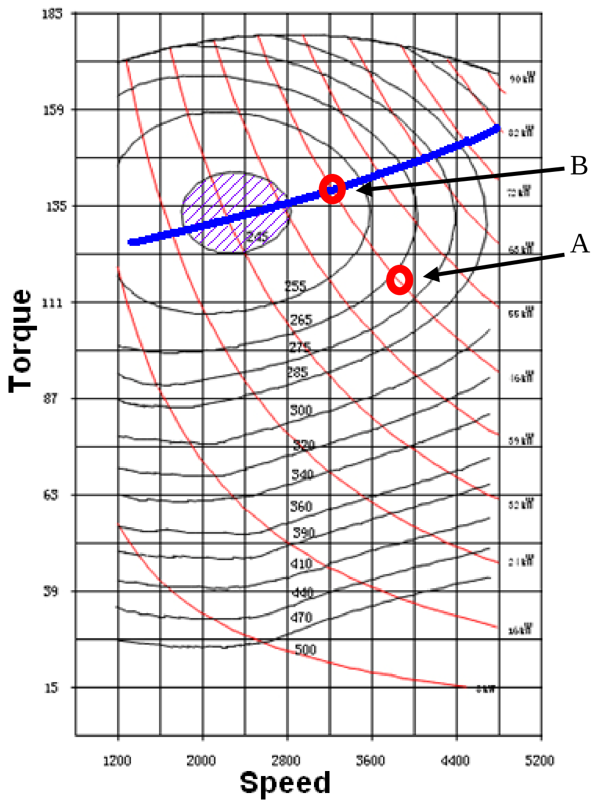

Figure 2: Engine Efficiency Map and Optimal Operating Line

Taking account of the mechanical / electrical energy transform and battery charge / discharge efficiency, and the wide range of driving load, the engine power output should track the driving requirement and minimize the energy transform. So the optimal operating points make a line, as the thick blue line shown in fig. 2. For example, if the vehicle requires operating at point A, and the battery doesn't need to be charged, point B----the intersection of optimal line and the equal-power curve which passes point A will be the engine operating point.

3.3 Motor

In dual rotor motor system, both the inner and outer rotor can work as a motor or generator. Again, torque-speed map is used here to describe the working modes of motor, as shown in fig. 3.

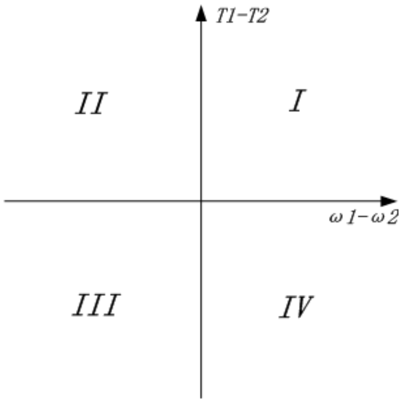

Figure 3: Motor Torque-Speed Map

In fig.3, (*ω1, T1*) and (*ω2, T2*) are speed and torque of outer and inner rotor respectively.

3.3.1 Inner rotor

The inner rotor working mode is determined according to the difference between *ω1 and ω2.*

- *ω1= ω2*: two rotors are synchronous. No power is generated or absorbed by the inner rotor;
- *ω1< ω2*: Inner rotor rotates faster than outer rotor. So it works as a generator, transforming part of power from the engine from mechanical to electrical;
- *ω1> ω2*: Inner rotor rotates more slowly than outer rotor. So it works as an asynchronous motor, transforming energy from electrical to mechanical;

3.3.2 Outer rotor

The outer rotor working mode is determined according to the difference between *T1 and T2.*

- *T1=T2*: the output torque is totally coupled from inner motor;
- *T1<T2*: the output torque is smaller than that coupled from inner rotor, so outer rotor works as a generator, transforming part of power from mechanical to electrical;
- *T1>T2*: the output torque is greater than that coupled from inner rotor, so outer rotor works as a synchronous motor, transforming energy from electrical to mechanical;

3.4 Battery

The control strategy for battery is to keep the battery's SOC in its high efficiency area and guarantee SOC does not fall below the lowest or exceed the highest acceptable value, as shown in fig. 4.

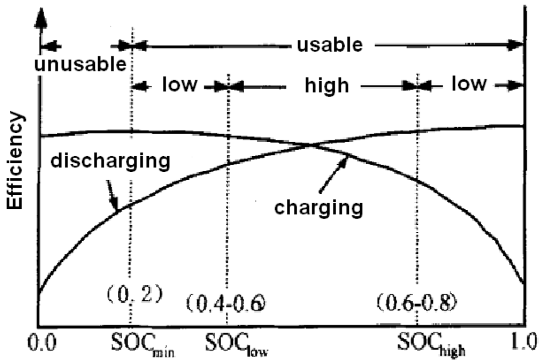

Figure 4: Battery efficiency

When charging the battery, to avoid over charge and to remain capability of store energies from regenerative braking, the SOC upper limit is set to 80% and the charging power can be calculated as:

$$\mathrm{SOC_{upper}} = 0.8$$

$$\mathrm{P_{charge}} = \begin{cases} \mathrm{P_{max\ charge}} \times \dfrac{\mathrm{SOC_{upper}} - \mathrm{SOC}}{\mathrm{SOC_{upper}}} & \mathrm{SOC} < \mathrm{SOC_{upper}} \\ 0 & \mathrm{SOC} \geq \mathrm{SOC_{upper}} \end{cases}$$

When the SOC is below the lower limit 0.20 the engine will start-up immediately to drive the vehicle and charge the battery, no matter how its efficiency will be.

3.5 Power management

If we neglect power losses during transformation and transfer to simplify the discussion, the power balancing equation of the HEV system is as blow:

$$P_{Veh}=P_{ICE}+P_{Bat} \qquad (1)$$

The required driving power P_{Veh} can be identified from the position and changing speed of acceleration pedal, which represents the driver's driving purpose. The battery power P_{Bat} is determined by its SOC. Thus the third value, the engine power, P_{ICE} can be calculated from equation (1). And through the optimal operating line in fig.

2, the speed and torque of engine can be found out. If the P_{ICE} is too small and cannot find a matching point on the optimal operating line, the engine will stop and the vehicle becomes a pure electric vehicle.

4 Simulation

A simulation model is developed in Matlab environment to evaluate the system configuration and control strategy discussed above. The model consists of seven modules: body, battery, motor, ICE, driver, vehicle control and drive cycle, as shown in fig. 5.

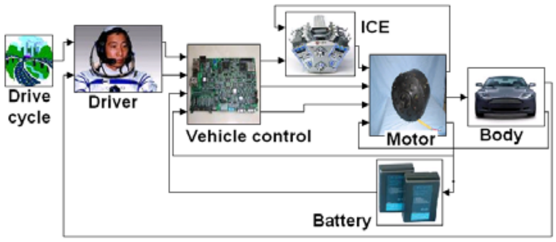

Figure 5: simulation model

The engine and motor is modelled with their efficiency map respectively. As the elementary step of the simulation, rather than using those complex drive cycles, a customized simple drive cycle is adopted, only containing one accelerating and decelerating process (fig. 6).

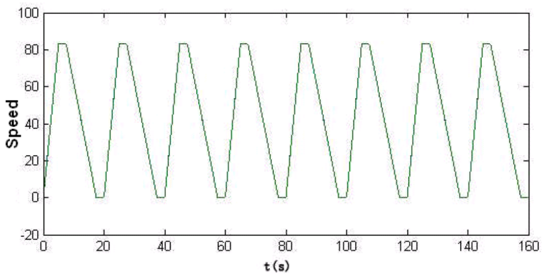

Figure 6: drive cycle in simulation

One characteristic of the control strategy is that it can automatically adjust the power distributing policy so that the SOC tend to remain at a certain value. In the simulation, it's set to 0.75. Fig. 7 shows the SOC-time history curve when the initial SOC is 0.75. At the end of each cycle, the SOC is very close to 0.75.

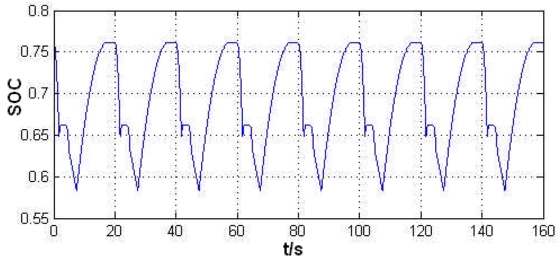

Figure 7: SOC-time history (SOC0=0.75)

Fig.8 and fig.9 show the SOC-time curve when the initial value is 0.9 and 0.4. As shown in these figures, the charging power to the battery pack is adjusted according to current SOC. As a result, after a few cycles, the SOC gradually reaches the preset value: 0.75 at the end of each cycle.

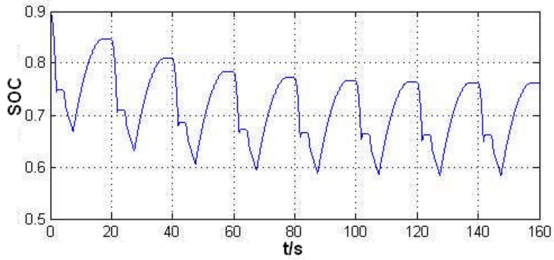

Figure 8: SOC-time history (SOC0=0.90)

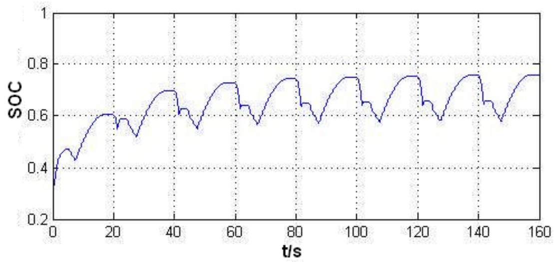

Figure 7: SOC-time history (SOC0=0.40)

The fuel economy of the Hybrid SUV is also calculated using the simulation model, with an initial SOC value 0.75. 1728 g gasoline is used in 100 cycles, equivalent to 10.4 L/100KM. Since the SOC at the end of simulation is very close to that at the beginning, this value can represent the total energy consumption of the process. As a contrast, the original conventional SUV with same engine will use up 2335g gasoline in 100 cycles, or 14.1 L/100KM. That means the introduction of hybrid techniques leads to an increase of 26% in fuel economy.

5 Conclusions

A distinctive HEV system is presented. The adoption of dual rotor motor system enables the

engine to operate at its optimal operating points independent to driving load.
The system configuration and control strategies of engine, motor and battery are discussed.
Simulations model of the system is developed to evaluate the control strategies. Simulation results show: 1) the control strategy can automatically adjust the power distributing policy so that the SOC tend to remain at a preset value; 2) the prototype SUV can save fuel up to 26% in certain drive cycle compare to the original conventional SUV.

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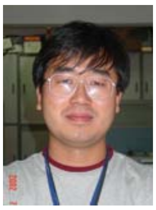
Authors



Prof. Yongchang DU was born in September 1971 in north China’s Hebei Province. He entered Tsinghua University in 1988 and received his doctor’s degree in 1999. Since then, he joined Tsinghua Automotive Engineering Institute (TAEI). His research interest includes HEV control strategy and optimization method, modal analysis and test, fatigue prediction, tire dynamics and NVH software development, etc.