

## Hybrid Electric SUV Based on Dual Rotor PM Motor

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### 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*

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## 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 Fuel Conservation at Tsinghua University have been working on various HEV projects for more than two decades. This paper presents some efforts from a current on-going project support by the National High-tech R &D program (863 program) 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.

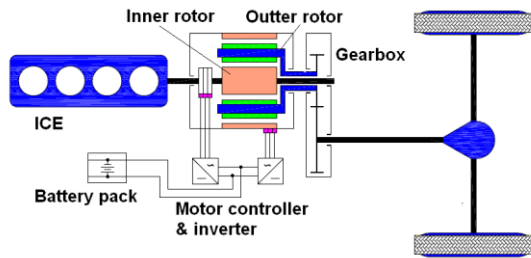


Figure 1: System Configuration

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.

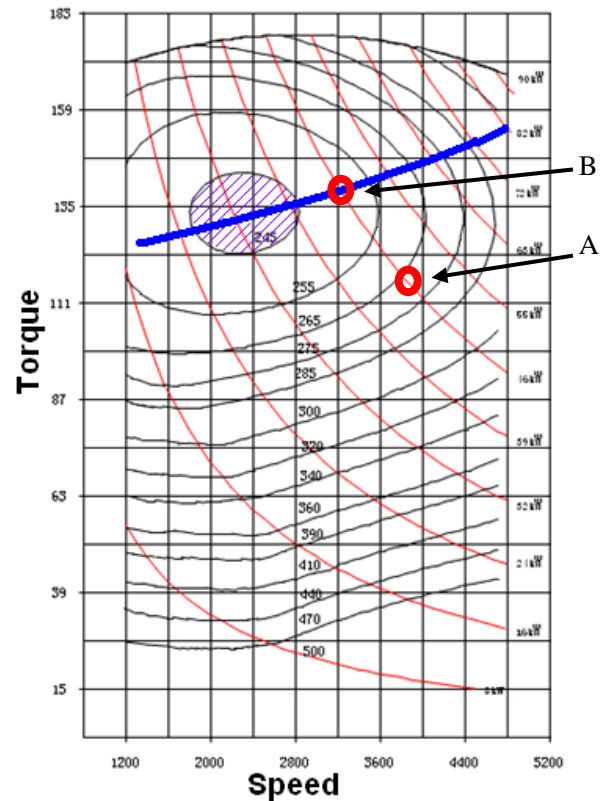


Figure 2: Engine Efficiency Map and Optimal Operating Line

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.

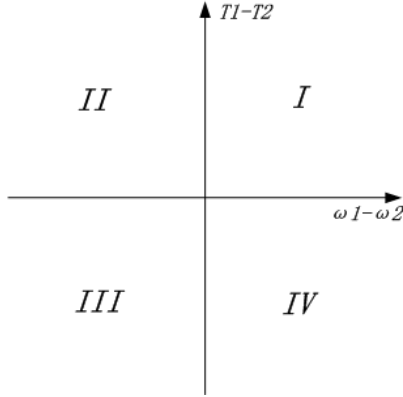


Figure 3: Motor Torque-Speed Map

In fig.3,  $(\omega 1, T1)$  and  $(\omega 2, T2)$  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  $\omega 1$  and  $\omega 2$ .

- $\omega 1 = \omega 2$ : two rotors are synchronous. No power is generated or absorbed by the inner rotor;
- $\omega 1 < \omega 2$ : Inner rotor rotates faster than outer rotor. So it works as a generator, transforming part of power from the engine from mechanical to electrical;
- $\omega 1 > \omega 2$ : 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.

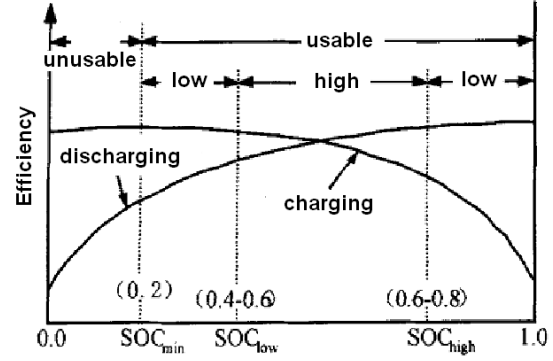


Figure 4: Battery efficiency

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

$$SOC_{upper} = 80\%$$

$$P_{charge} = \begin{cases} P_{max\ charge} \times \frac{SOC_{upper} - SOC}{SOC_{upper}} & SOC < SOC_{upper} \\ 0 & SOC \geq SOC_{upper} \end{cases} \quad (2)$$

When the SOC is below the lower limit 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:

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

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

Using the control strategy discussed above, simulations is carried out for ECE15 drive cycle. The engine and motor is modelled with their efficiency map respectively. The original conventional SUV with same engine is also calculated. Typical fuel consumption results are shown .

## 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 of the system show that the prototype SUV can save fuel up to 20% in ECE15 driving cycle, compare to the original conventional SUV.

Referencing sources in the paper shall be done with sequential numerical references, between square brackets.

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