

A Novel Series-parallel Power Train for Hybrid Electric Vehicle Applications

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Abstract

As a novel series-parallel power train, electric variable transmission (EVT) has attracted increased interests in recent years because of its high level integration and the advantages in improving fuel economy and reducing emissions. This paper will briefly introduce this novel power train and put more emphasis on its applications in hybrid electric vehicle (HEV) including modeling, simulation and experimental study. The work is helpful to design EVT, analyze the power flows of an EVT based HEV, and make the control strategy. Energetic Macroscopic Representation (EMR) is used in the global modeling for the EVT based HEV, and a control scheme is deduced from EMR models using specific inversion rules.

Keywords

electric variable transmission, hybrid electric vehicle, induction machine, energetic macroscopic representation, modeling, control

1. INTRODUCTION

A hybrid electric vehicle (HEV) combines a conventional propulsion system with one or more secondary energy storage sources, such as a battery, fuel cell, or ultracapacitor, to provide the vehicle power. Traditionally, HEV has three categories: series hybrid, parallel hybrid, and series-parallel hybrid. The series-parallel hybrid, also known as power-split hybrid, takes the advantages of both series and parallel hybrid, and performs more efficient and more complicated [Liu et al., 2008]. Some modern HEVs prefer this configuration, such as the bestselling Toyota Prius HEV [Chan, 2004]. The core of Toyota Prius is its power train called Toyota Hybrid System (THS). Connecting an internal combustion engine (ICE) with two electric machines, a planetary gear enables the function of power split and propels the vehicle. At present, Prius has an improved power train version (THS II) with enhanced efficiency and greater power.

A novel HEV power train, known as electric variable transmission (EVT) has been introduced recently [Hoeijmakers et al., 2006] and attracted increased interests [Cheng et al., 2007] because of its high level integration and the advantages in improving fuel economy and reducing emissions. The EVT based HEV is a simpler series-parallel hybrid.

In Section 2, this paper will briefly introduce this novel power train. In Section 3, the mathematical model of EVT will be given. After that, the global modeling

of an EVT based HEV using Energetic Macroscopic Representation (EMR) is built, and the control deduced from EMR models is presented. Simulation results, test bench and results are given in Section 4.

2. STRUCTURE OF EVT

EVT is composed of stator, inner rotor and outer rotor shown in Figure 1. The outer rotor has two separate squirrel cages on its inner and outer surfaces. The stator has three phase windings and is fed by inverter 1 (INV1). The inner rotor has also three phase windings on it and is fed by inverter 2 (INV2) through sliprings. In principle, EVT could be seen as a combination of an inner machine EM1 consisting of inner rotor and inner cage on the outer rotor, and an outer machine EM2 consisting of stator and outer cage on the outer rotor. But because of the thin yoke height of outer rotor, a coupling exists between two airgap fields and changes with different loads. A field distribution of

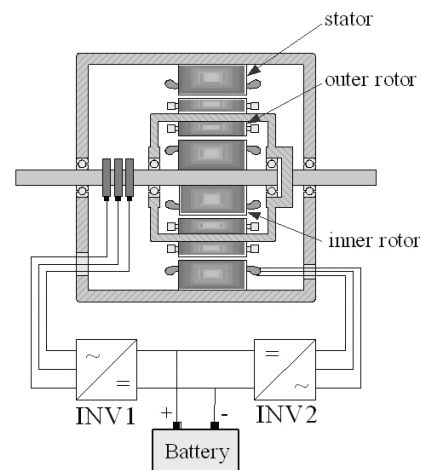


Fig. 1 Electric variable transmission

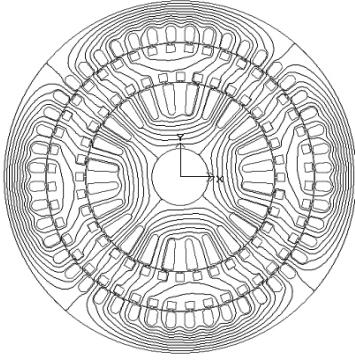


Fig. 2 The field distribution of EVT

EVT is shown in Figure 2.

For the sake of simplification, the following analysis will be based on a split EVT and only mechanical connection exists in it. An HEV equipped with a split EVT is shown in Figure 3. The power produced by ICE is divided into two parts at EM1. One part, shown as P_d , passes directly to EM2 through the EM1 electromagnetic field. The other, shown as P_e , is electrical power and also reaches to the EM2 through two inverters. The battery could discharge or be recharged depending on the required vehicle power and optimized ICE power.

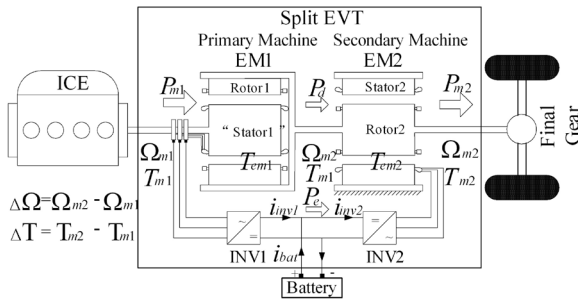


Fig. 3 The split EVT based HEV

3. SYSTEM MODELING

3.1 Mathematical model of split EVT

EM2 can use the mature mathematical model of induction machine as reference. EM1 could be considered as a normal induction machine with the exception that the “stator” is rotating and placed inside. If d-axis is aligned with the flux of the outer rotor, the EM1 model is as follows. The voltage equations are

$$\begin{cases} u_{s1_d} = R_{s1}i_{s1_d} + \frac{d}{dt}\psi_{s1_d} - (\omega_{s1} - n_p \cdot \Omega_{m1})\psi_{s1_q} \\ u_{s1_q} = R_{s1}i_{s1_q} + \frac{d}{dt}\psi_{s1_q} + (\omega_{s1} - n_p \cdot \Omega_{m1})\psi_{s1_d} \\ u_{r1_d} = 0 = R_{r1}i_{r1_d} + \frac{d}{dt}\psi_{r1_d} \\ u_{r1_q} = 0 = R_{r1}i_{r1_q} + \omega_{r1}\psi_{r1_d} \end{cases} \quad (1)$$

The equations of flux linkage are

$$\begin{cases} \psi_{s1_d} = L_{s1}i_{s1_d} + M_{s1r1}i_{r1_d} \\ \psi_{s1_q} = L_{s1}i_{s1_q} + M_{s1r1}i_{r1_q} \\ \psi_{r1_d} = L_{r1}i_{r1_d} + M_{s1r1}i_{s1_d} \\ \psi_{r1_q} = L_{r1}i_{r1_q} + M_{s1r1}i_{s1_q} \end{cases} \quad (2)$$

The synchronous speed and slip speed are

$$\omega_{s1} = n_p \cdot \Omega_{m1} + 2\pi f_1 = n_p \cdot \Omega_{m2} + \omega_{r1} \quad (3)$$

$$\omega_{r1} = s_1 \cdot \omega_{s1} = \frac{M_{s1r1}}{\tau_{r1}} \frac{i_{s1_q}}{\psi_{r1_d}} \quad (4)$$

The electromagnetic torque equation is

$$T_{em1} = n_p \frac{M_{s1r1}}{L_{r1}} \psi_{r1_d} i_{s1_q} \quad (5)$$

Here, the subscript 1 represents for EM1 machine. It is assumed that both EM1 and EM2 have the same number of pole pairs n_p . $i_{s1_d,q}$ and $i_{r1_d,q}$ are the d, q currents of “stator 1” and rotor 1. Ω_{m1}, Ω_{m2} are the mechanical speeds of inner and outer rotor, R_{s1}, L_{s1} the resistance and self inductance of “stator 1”, R_{r1}, L_{r1} the resistance and self inductance of rotor 1 respectively, M_{s1r1} the mutual inductance, and $\tau_{r1} = L_{r1}/R_{r1}$ the rotor electrical time constant. f_1 is the current frequency of “stator 1”.

3.2 Global modeling and control

To investigate the operating characteristics of EVT and develop the energy control strategy, a global modeling of a split EVT based HEV is built.

EMR is used to build the global model in this paper. Introduced in 2000, EMR has been used to describe complex electromechanical systems, such as HEV system, wind power system, etc (see Appendix). As an energy-based graphical modeling tool, EMR helps to understand deeply the energetic properties of a system. Using inversion based rules, a control scheme could be systematically deduced from this modeling tool and put into experiments with minor modifications. The basics of EMR methodology and its inversion based control could be seen in [Chen et al., 2008].

On the basis of [Cheng et al., 2008] and [Chen et al., 2008], the global model and control scheme of the EVT based HEV are built, which is illustrated in Figure 4.

3.3 Energy control strategy

In the EVT based HEV, ICE is not connected to the vehicle, which results in the independent operation of

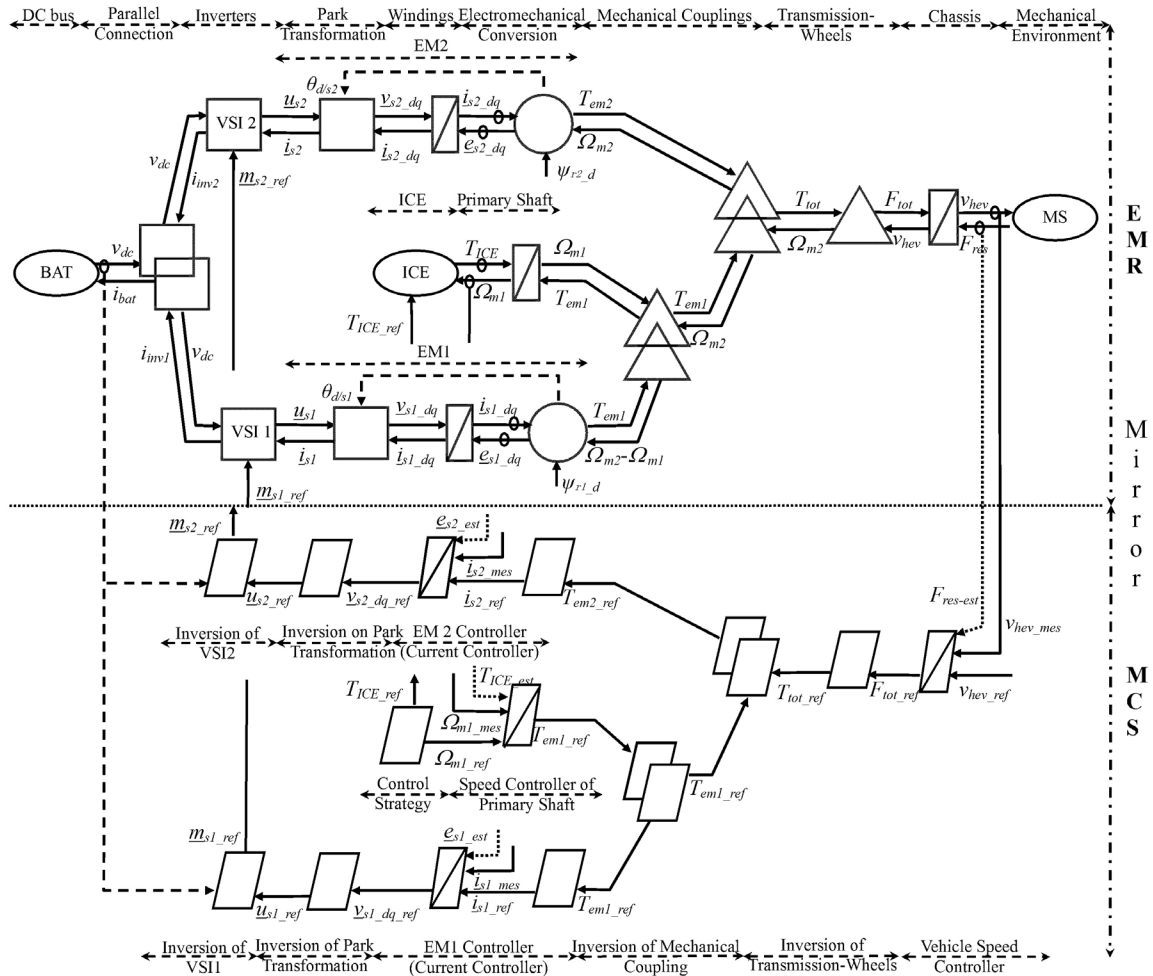


Fig. 4 Global EMR of split EVT based HEV and its inversion-based control

ICE on the road. A power follower control strategy has been studied to optimize the ICE operation [Cheng, 2008]. To implement such a strategy, EM1 adopts speed control to change the speed by $\Delta\Omega$ from the speed required at the final gear to the optimal speed of the ICE. In the same manner, the torque is changed by ΔT with EM2 from the torque required at the final gear to the optimal torque of the ICE.

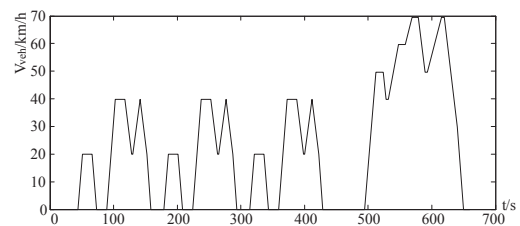
4. SIMULATION RESULTS AND EXPERIMENTS

4.1 Simulation results

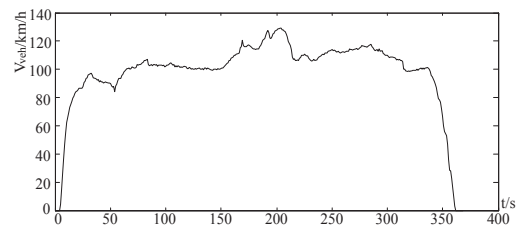
HEV system simulation is carried out in Matlab/Simulink environment under 10.15 urban cycle and US06 highway cycle. Two driving cycles are shown in Figure 5. Simulation results are shown in Figures 6-8. From the simulation results, statistical analysis is done to achieve the EVT design guidelines as Table 1. Also, the working features of EM1 and EM2 could be summarized as follows:

- (1) EM1 torque follows closely the ICE torque output. EM2 speed is proportional to vehicle speed.
- (2) In highway cycle, EVT power and torque require-

ments are higher and the distribution of working points is more concentrated than those in urban cycle. In urban cycle, EM1 and EM2 should have

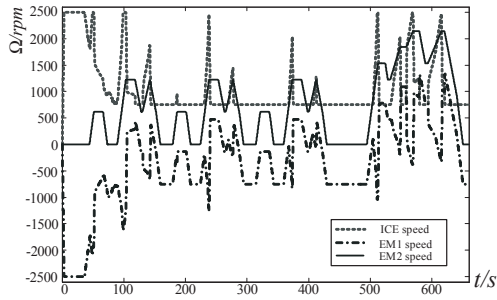


(a) 10.15 urban driving cycle

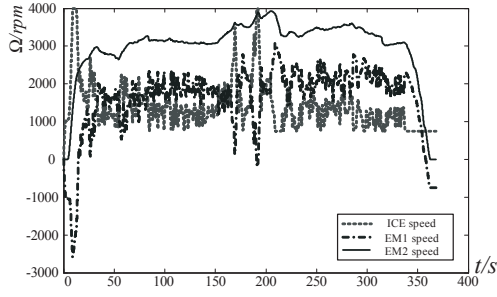


(b) US06 highway driving cycle

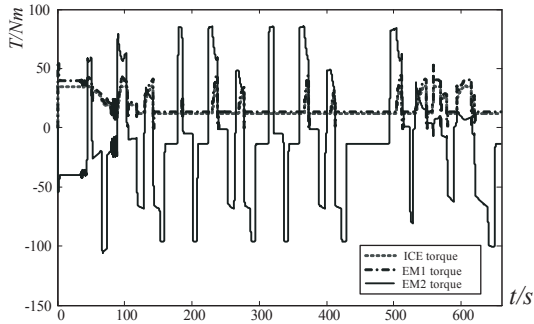
Fig. 5 Driving cycles for the split EVT based HEV simulation



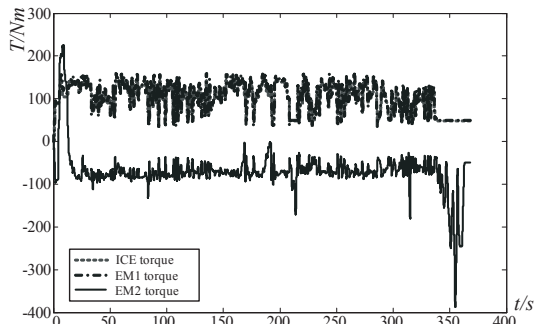
(a) 10.15 cycle



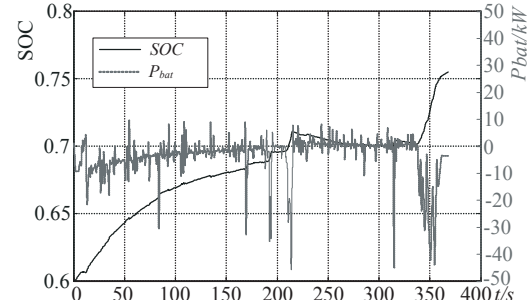
(b) US06 cycle

Fig. 6 The operating speed curves of EM1, EM2 and ICE under 10.15 and US06 cycles

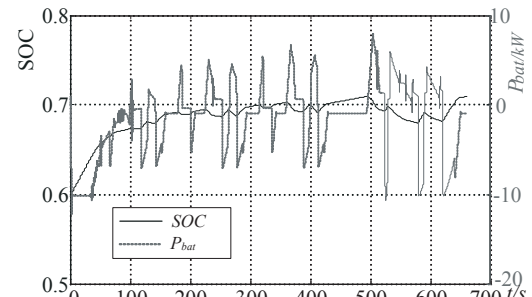
(a) 10.15 cycle



(b) US06 cycle

Fig. 7 The operating torque curves of EM1, EM2 and ICE under 10.15 and US06 cycles

(a) 10.15 cycle



(b) US06 cycle

Fig. 8 Battery power and SOC curves**Table 1** EVT design guidelines

	10.15 cycle		US06 cycle	
	EM1	EM2	EM1	EM2
Rated Speed (rpm)	750	1200	2000	3250
Rated Torque (Nm)	15	25	130	80
Rated Power (kW)	1.5	3.2	27	27
Max Speed (rpm)	2500	2200	3000	3750
Max Torque (Nm)	45	110	160	400
Max Power (kW)	10	12	40	60

high efficiency over wider speed and torque ranges, especially in the small power range.

- (3) In general, EM2 has higher power and instant overload capacity than EM1 to satisfy vehicle dynamic performance. Besides, EM2 should have high efficiency in regenerative braking mode.
- (4) In urban cycle, EM1 torque distribution concentrates in low range and should have high instant overload capacity. In highway cycle, EM1 torque distribution range is wider.

In 10.15 and US06 driving cycles, the simulated fuel economies are 4.87 L/100 km and 4.33 L/100 km, respectively. Compared with a convention vehicle, the

fuel economy is increased by 23 % and 32 % respectively.

4.2 Experiment of a split EVT based HEV

A test bench for a split EVT based HEV was built as shown in Figure 9. ICE and road load are replaced by two 40 kW induction machines named EM0 and EM3. EM1 and EM2 are a 20 kW and a 10 kW induction machine. The control system adopts the modular system containing a CPU board and some I/O boards from dSPACE. On the basis of Matlab/Simulink and dSPACE platform, the EMR based control scheme in Section 3 is applied into the bench with minor modifications.

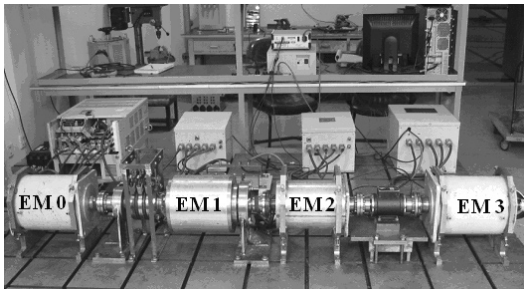


Fig. 9 The test bench for a split EVT based HEV

Only 10.15 cycle is simulated in this test bench. The speed and torque commands are downsized to match the bench output ability. Some experimental results are shown as Figure 10.

5. CONCLUSION

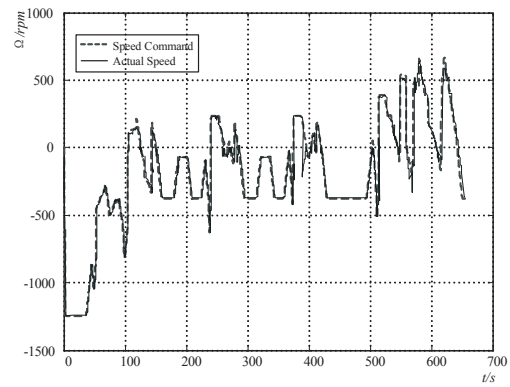
This paper studies the applications of a novel series-parallel power train in HEV. EVT structure and working principle are briefly introduced. Global modeling and simulation based EMR have been carried out in Matlab/Simulink environment. Test bench for a split EVT based HEV is built. The simulation and experimental results prove that EVT could not only satisfy the vehicle performance but also optimize ICE operation. Fuel consumption is reduced greatly compared to a conventional vehicle. The simulation also provides reference for designing EVT and analyzing the operation characteristics of ICE and EVT.

Acknowledgement

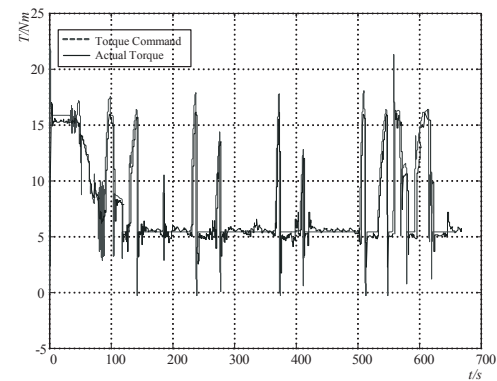
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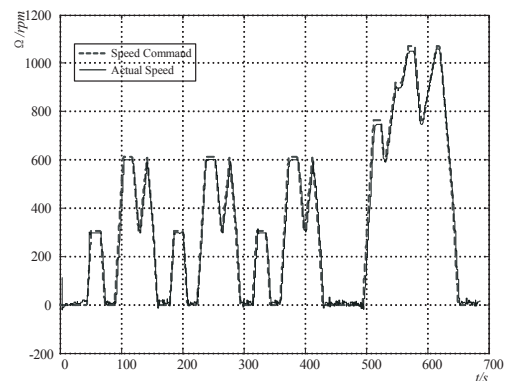
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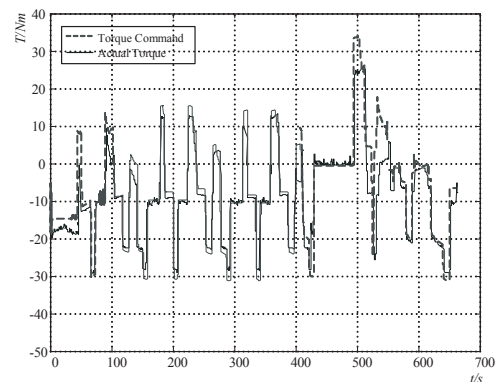
(a) EM1 speed test results



(b) EM1 torque test results



(c) EM2 speed test results




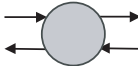
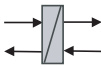
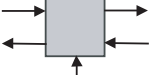
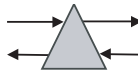
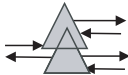
(d) EM2 torque test results

Fig. 10 The test results of a split EVT based HEV system under 10.15 driving cycle

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Appendix Synoptic of energetic macroscopic representation

	Source of energy		Electromechanical converter (without energy accumulation)		Element with energy accumulation
	Electrical converter (without energy accumulation)		Mechanical converter (without energy accumulation)		Coupling device (distribution of energy)