# Power Distribution and Coordinated Control for a Power Split Hybrid Electric Bus

**Feng Wang*, Hu Zhong, Zi-Lin Ma, Xiao-Jian Mao and Bin Zhuo**

**Abstract** – The power distribution is proposed to determine the target operating points of the system components as the basis for maximal the efficiency of the overall system for a power split dual electric machine hybrid electric bus. The coordinated control is constructed on the basis of the power distribution. The basic coordinated control is implemented to satisfy the driver's power demand, in which both the dynamic characteristics of the engine and the dual electric machine are explicitly taken into account. Moreover, the improved coordinated control is suggested to suppress engine dynamic operation and rich fuel injection.

**Keywords:** Power Split, Hybrid electric bus, Power distribution, Coordinated control

## 1. Introduction

Hybrid electric vehicle (HEV) is considered to offer the best promise in the short term to mid-term. The impact on the fuel economy generally improves by more than 50% in heavy traffic for the power split HEV [1-2]. Nowadays, the Toyota Prius [3] is the representative power split HEV; however, the mechanical components are very complex and expensive. It is difficult to compensate the high cost by the fuel save. Therefore, a power split dual electric machine (DM) hybrid electric bus is investigated, which is unique in the sense that no complex mechanical components are needed, but still the advantages of the power split HEV are exploited.

As the deeply research for the HEV control issues, people paid more and more attention to the coordinated control issue for the coupling process among different energy sources and have been introduced some control approaches for the parallel HEV [4-7].

For the system components, the current research has three aims: to formulate an e power distribution to determine the target operating point of the system components; to develop a basic coordinated control to satisfy the driver's power demand; to propose an improved coordinated control to suppress engine dynamic operation and rich fuel injection.

* School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai, China. (wf51@sjtu.edu.cn)
Received 7 April 2008 ; Accepted 22 October 2008

## 2. Hybrid Electric Bus

The configuration of the power split dual electric machine hybrid electric bus is illustrated in Fig. 1.

The internal combustion engine (ICE) flywheel, the mechanical clutch and the manual transmission fixed in a conventional bus are replaced by the DM, a dynamic servo unit, a booster unit and batteries pack in the hybrid electric bus. The DM consist of one generator and one motor, and work as an electromagnetic clutch and a continuously variable transmission simultaneously. Dual buses, which consist of low and high voltage bus, and the booster unit is used to enhance the DM work voltage and efficiency. The function of the dynamic servo unit is shown in Fig. 2.

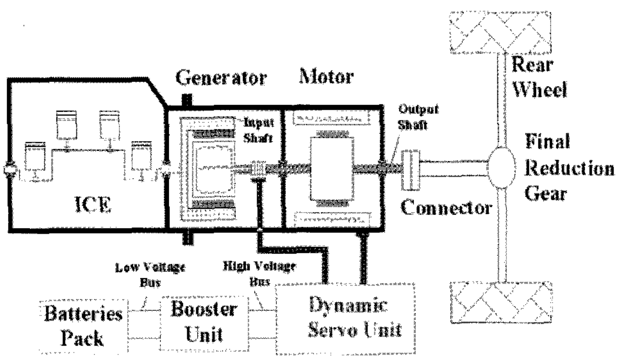



**Fig. 1.** Configuration of the power split dual electric machine hybrid electric bus

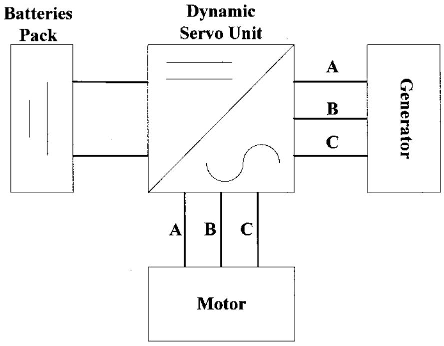



**Fig. 2.** Function of the dynamic servo unit

The DM are concentrically arranged [8-9] and mounted between an ICE and a final reduction gear. The generator rotor is directly connected to the ICE crankshaft defined as the input shaft. The generator stator is connected to the dynamic servo unit via slip-rings and brushes, and it is mechanically directly connected to the motor rotor defined as the output shaft. The motor stator is fixed in the vehicle chassis and also connected to the dynamic servo unit. The output shaft is connected to the final reduction gear via a connector.

The DM control the ICE independent of the road load and change both the speed and torque produced by the ICE at the operating point determined by the ICE operation control to the required speed and torque at the final reduction gear. The generator changes the speed from the ICE $n_{\mathrm{ICE}}$ to the speed required at the final reduction gear $n$, and delivers the same torque as the ICE. The motor changes the torque produced by the ICE $T_{\mathrm{ICE}}$ to match the demanded torque at the final reduction gear $T$, and operates at the same speed as the speed at the final reduction gear. There are four different operation modes for the hybrid electric system.

The parameters of the vehicle and system components are presented as follows: vehicle mass is 9 375 kg; drag coefficient is 0.7; frontal area is 7 m$^2$; tire radius is 0.445 m; final drive ratio is 5.714; rolling resistance coefficient is 0.0092; ICE maximal torque is 300 N.m; ICE maximal power is 85 kW; generator maximal power is 55 kW; generator base speed is 1 500 r/min; motor maximal power is 113 kW; motor base speed is 1 200 r/min; rated voltage of batteries pack is 312 V; batteries pack capability is 45 Ah.

## 3. Power Distribution

Power distribution and coordinated control are two main control issues for the hybrid electric system, and the coordinated control is constructed on the basis of the power distribution.

The vehicle power request $P_{\mathrm{req}}$ (at the final reduction gear) is the sum of the positive drive power according to the accelerator pedal position and the negative brake power according to the brake pedal position[10]. A simple PI controller is used to calculate the current batteries pack charging power request $P_{\mathrm{ch}}$ to keep the batteries pack SOC around the target value over the driving cycles. Then, the demanded power at the final reduction gear $P$ can be expressed as

$$P = P_{\mathrm{req}} + P_{\mathrm{ch}} \tag{1}$$

The vehicle operation modes can be divided into the driving and braking modes according to the value $P$.

For the driving mode, when the ICE power is smaller or larger than threshold values, the ICE efficiency is much smaller. Therefore, the driving mode can be divided into the following three sub-modes: ① When $P<$ 21 kW, the ICE is directed to stop fuel injection and the vehicle is operating in pure electric mode. During this sub-mode, the motor target torque $T_{\mathrm{Mo}}$ can not bigger than the motor maximal motoring torque under the restriction of the batteries pack maximal discharging power. ② When 21 kW $\le P \le$77 kW, the ICE provides the demanded power alone; ③ When $P>$77 kW, the ICE power is restricted to 77 kW, and the batteries pack supply the power whatever is left over.

For the braking mode, if the torque required at the final reduction gear is smaller than the motor maximal generation torque under the restriction of the batteries pack maximal charging power, the motor regenerative torque is not sufficient enough to achieve the demanded driven wheel braking torque, then the electronic pneumatic brake system works simultaneously to supply the insufficient force [10].

Using the vehicle parameters specified, the speed and torque required at the final reduction gear can be represented as

$$\begin{cases} n = 34V \\ T = \dfrac{9\,550 P_{\mathrm{req}}}{n} \end{cases} \tag{2}$$

where $V$ is the vehicle velocity, km/h.

For the hybrid electric system, the ICE operation control is the core problem of the power distribution, which should maximize the efficiency of the overall system $\eta_{\mathrm{S}}$, expressed as

$$\eta_S = \eta_{ICE}\eta_T \tag{3}$$

where $\eta_{ICE}$ is the ICE efficiency. $\eta_T$ is the DM transmission efficiency, represented as

$$\eta_T = \frac{P_{req}}{P + P_B} \tag{4}$$

where $P_B$ is the batteries pack electric power drawn or supplied and can be obtained according to the internal resistance model, shown in Fig. 3.

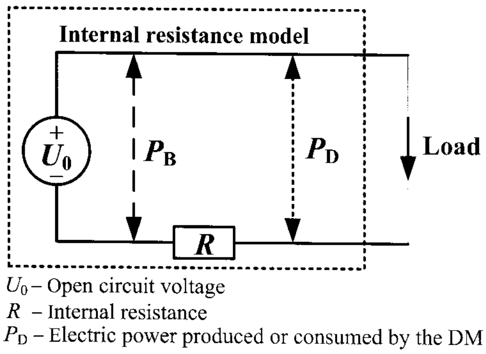



**Fig. 3.** Internal resistance model of the batteries pack

For the different combination of the DM operation modes, the variable $P_D$ can be represented as

$$\begin{cases} P_D = P_{Mo}C_{Mo} + P_{Ge}C_{Ge} \\ C_{Mo} = \begin{cases} \eta_{Mo}\eta_C & P_{Mo} < 0 \\ 1/(\eta_{Mo}\eta_C) & P_{Mo} \geq 0 \end{cases} \\ C_{Ge} = \begin{cases} \eta_{Ge}\eta_C & P_{Ge} < 0 \\ 1/(\eta_{Ge}\eta_C) & P_{Ge} \geq 0 \end{cases} \end{cases} \tag{5}$$

where $\eta_{Ge}$ is the generator efficiency, $\eta_{Mo}$ is the motor efficiency. They can be obtained according to the DM efficiency contours. $\eta_C$ is the efficiency of the dynamic servo unit, which is assumed constant (e.g. 0.95).

The ICE operation control is designed to find the ICE optimal speed $n_{opt}$ and torque $T_{opt}$ with maximal $\eta_S$, represented as

$$(n_{opt}, T_{opt}) = \arg\max \eta_S \tag{6}$$

Once the ICE operating point is determined by the above-mentioned method, the DM operating points are also subsequent decided, shown in Fig. 4.

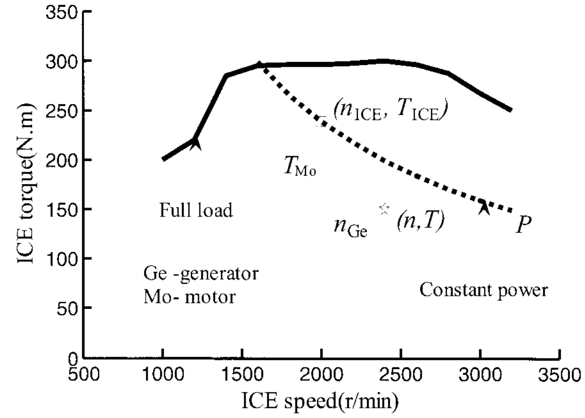



**Fig. 4.** Diesel characteristics and work principle

## 4. Coordinated Control

### 4.1 Dynamic Characteristics

Because of the mechanical inertia, the inner heat inertia and the combustion deterioration, the ICE dynamic performance (torque) deviates from the steady-state performance [11]. There exists an obvious delay and lag phenomenon for the ICE from one former to another new target torque, and the ICE torque response lag equals several hundred milliseconds. Fig. 5 shows the ICE actual torque when the target torque increases and decreases from $T_1$ to $T_2$ respectively.

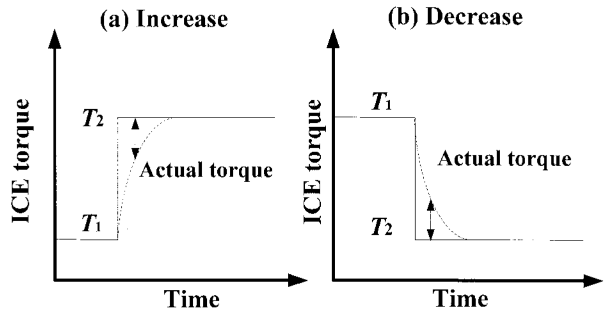



**Fig. 5.** ICE torque response lag

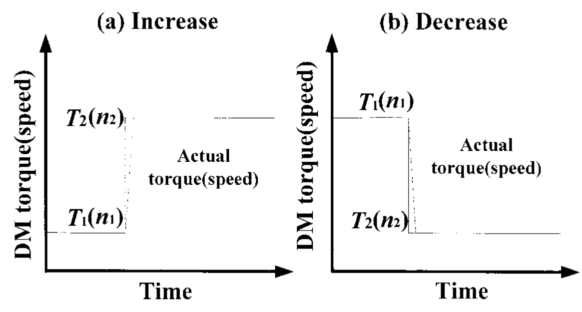



**Fig. 6.** DM torque or speed response lags

The generator speed and the motor torque can achieve the closed-loop control by the vector-control method, and the DM dynamic response lags reaching to their corresponding target values only need several milliseconds. Fig. 6 shows the DM actual torque or speed when the target torque or speed increases and decreases from $T_1$ ($n_1$) to $T_2$ ($n_2$) respectively.

Therefore, the DM response rates are very quick and the DM response lags can be neglected compared with the ICE.

### 4.2 Problem Definition

The favorable dynamic process control is one of the key techniques for industrializing the HEV.

The power distribution is developed as the basis for the static efficiencies characteristics of the system components, whose main problem does not take their dynamic characteristics into account. If the dynamic characteristics of the ICE and the DM are the same, the actual output torque at the final reduction gear can satisfy the driver's power demand.

However, because of mode-switch or power request variation, abrupt variation of the ICE target operating point by the power distribution results in rapid changing of the DM target operating points. The target operating points of the system components according to the power distribution are difficult to carry out, and there appears a large warp between the actual and request torques at the final reduction gear due to the significant dynamic characteristic difference between the ICE and the DM. Such a phenomenon eventually results in a huge instability of the power transfer, affects the power performance and deteriorates the drivability.

### 4.3 Basic Coordinated Control

The DM dynamic characteristic is the basis of the coordinated control. Before the ICE and DM reach the new target operating points themselves, the basic coordinated control for the system components must be implemented to satisfy the driver's power demand, which is a control issue of power performance and driving comfort.

The hybrid control unit (HCU) sends the control instruction of the ICE target throttle $\alpha_{Tar}$, which is gained by using the part throttle characteristics map according to the target speed and torque by the power distribution, to the ICE management system (EMS) in order to make the ICE reach new target operating point, therefore the ICE throttle by the basic coordinated control $\alpha_{Basic}$ can be expressed as

$$\alpha_{\text{Basic}} = \alpha_{\text{Tar}} = f(n_{\text{ICE}}, T_{\text{ICE}}) \tag{7}$$

where $f$ is the function of the ICE part throttle characteristics by using the diesel engine test bench data.

However, it can not achieve the closed-loop control of the ICE target operating point by above-mentioned method, thus the open-loop control is used to manage the ICE operating point.

Because of the generator, the ICE can reach its target speed $n_{ICE}$ immediately, thus the generator target speed by the basic coordinated control $n_{Ge\_Basic}$ can be gained by subtracting the ICE target speed from the speed required at the final reduction gear, expressed as

$$n_{\text{Ge\_Basic}} = n - n_{\text{ICE}} \tag{8}$$

Because of the ICE torque response lag, if the motor is still controlled by the motor target torque according to the power distribution, the sum of the ICE and motor actual output torques will be significant different from the torque required at the final reduction gear. Because the motor can generate torque more quickly than the ICE, the problem can be solved by the motor torque compensation. The difference between ICE target and actual torques can be compensated by the motor torque, and the magnitude of the motor compensatory torque by the basic coordinated control $T_{Com\_Basic}$ can be represented as

$$T_{\text{Com\_Basic}} = T_{\text{ICE}} - T_{\text{ICE\_Act}}(\alpha_{\text{Basic}}) \tag{9}$$

where $T_{ICE\_Act}$ is the ICE actual torque. Moreover, $T_{Com\_Basic}$ is positive when the ICE target torque increases, while negative when the ICE target torque decreases.

The generator actual torque $T_{Ge\_Act}$ equals the ICE actual torque, obtained as

$$T_{\text{ICE\_Act}} = T_{\text{Ge\_Act}} \tag{10}$$

And the value $T_{Ge\_Act}$ is transmitted from the generator control module to the HCU over the CAN bus.

The motor target torque by the basic coordinated control $T_{Mo\_Basic}$ can be gained by adding the $T_{Com\_Basic}$ to the motor target torque by the power distribution, represented as

$$T_{\text{Mo\_Basic}} = T_{\text{Com\_Basic}} + T_{\text{Mo}} \tag{11}$$

Using the equations 9-11,

$$T_{\text{Mo\_Basic}} = T - T_{\text{Ge\_Act}}(\alpha_{\text{Basic}}) \tag{12}$$

Therefore, the motor target torque by the basic coordinated control can be obtained by subtracting the generator actual torque from the torque required at the final reduction gear. Finally, the basic coordinated control can be expressed as the ICE target throttle open-loop control, the generator target speed control, the ICE actual torque feedback and the motor torque compensation, represented as

$$\begin{cases} \alpha_{\text{Basic}} = f(n_{\text{ICE}}, T_{\text{ICE}}) \\ n_{\text{Ge\_Basic}} = n - n_{\text{ICE}} \\ T_{\text{Mo\_Basic}} = T - T_{\text{Ge\_Act}}(\alpha_{\text{Basic}}) \end{cases} \tag{13}$$

## 4.4 Improved Coordinated Control

When the ICE target throttle increases abruptly, the ICE dynamic operation must be limited, because the ICE consumes disproportional amounts of fuel when making changes of operating point with a certain rate compared with the fuel consumption in stationary operation.

Therefore, the improved coordinated control is suggested to suppress engine dynamic operation and rich fuel injection, which can ensure ICE quasi-static operation.

The HCU does not send the control instruction of the ICE target throttle to the EMS directly, and the output control of the ICE throttle is restricted by the first order inertia link, whose dynamic equation can be represented as

$$M\frac{dc(t)}{dt} + c(t) = r(t) \tag{14}$$

where $M$ is the time constant. $r(t)$ and $c(t)$ are the input and output of the first order inertia link.

The variable $r(t)$ is the ICE target throttle increment, which is a step function and can be expressed as

$$r(t) = \alpha_2 - \alpha_1 \tag{15}$$

where $\alpha_1$ and $\alpha_2$ are the ICE target throttles of the former and current time segment respectively.

The variable $c(t)$ is the ICE control throttle $\alpha(t)$ expressed as a function of time $t$, which is the ICE throttle by the improved coordinated control $\alpha_{\text{Impro}}$ and can be obtained as

$$\alpha_{\text{Impro}} = \alpha(t) = \alpha_1 + (\alpha_2 - \alpha_1)(1 - \exp^{-\frac{t}{M}}) \tag{16}$$

The variable $\alpha_{\text{Impro}}$ increases from $\alpha_1$ to $\alpha_2$ till time reaches $3M$, and the error can eliminate by the boundary condition, gained as

$$\alpha(3M) = \alpha_2 \tag{17}$$

The time constant $M$ must be selected to ensure the ICE quasi-static operation, obtained as

$$M \geq \frac{\alpha_2 - \alpha_1}{3A} \tag{18}$$

where $A$ is the threshold of the ICE rich fuel injection. If equation 18 is satisfied, the ICE can suppress rich fuel injection.

The magnitude of the motor compensatory torque by the improved coordinated control $T_{\text{Com\_Impro}}$ can be represented as

$$\begin{cases} \Delta T = f^{-1}(n_{\text{ICE}}, \alpha_{\text{Basic}}) - f^{-1}(n_{\text{ICE}}, \alpha_{\text{Impro}}) \\ \quad = T_{\text{ICE\_Act}}(\alpha_{\text{Basic}}) - T_{\text{ICE\_Act}}(\alpha_{\text{Impro}}) \\ T_{\text{Com\_Impro}} = T_{\text{Com\_Basic}} + \Delta T \\ \quad = T_{\text{ICE}} - T_{\text{ICE\_Act}}(\alpha_{\text{Impro}}) \\ \quad = T_{\text{ICE}} - T_{\text{Ge\_Act}}(\alpha_{\text{Impro}}) \end{cases} \tag{19}$$

The motor target torque by the improved coordinated control $T_{\text{Mo\_Impro}}$ can be gained by adding the $T_{\text{Com\_Impro}}$ to the motor target torque by the power distribution, calculated as

$$\begin{aligned} T_{\text{Mo\_Impro}} &= T_{\text{Com\_Impro}} + T_{\text{Mo}} \\ &= T_{\text{ICE}} - T_{\text{Ge\_Act}}(\alpha_{\text{Impro}}) + T_{\text{Mo}} \\ &= T - T_{\text{Ge\_Act}}(\alpha_{\text{Impro}}) \end{aligned} \tag{20}$$

Fig. 7 illustrates the coordinated control blocks. Only the first order inertia link restriction block is added to the improved coordinated control compared with the basic coordinated control. Because the motor must compensate the toque loss for the slow increase of the ICE throttle, the motor torques by the improved coordinated control show bigger value than those of the basic coordinated control. Moreover, the durative time of the motor torque compensation is bigger for the improved coordinated control.

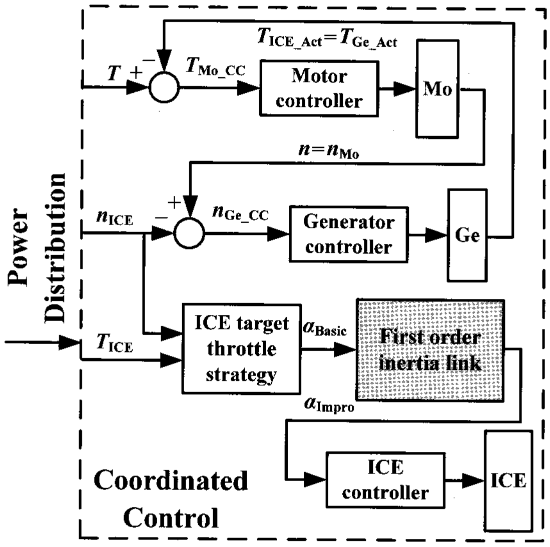



**Fig. 7** Coordinated control blocks

## 5. Conclusions

For a power split dual electric machine hybrid electric bus, the power distribution is proposed to determine the target operating points of the system components as the basis for maximal the efficiency of the overall system in all different operation modes. The coordinated control is constructed on the basis of the power distribution. The basic coordinated control is implemented to satisfy the driver's power demand, in which both the dynamic characteristics of the engine and the dual electric machine are explicitly taken into account. Moreover, the improved coordinated control is suggested to suppress engine dynamic operation and rich fuel injection.

## References

[1] C. C. Lin, H. Peng, J. W. Grizzle, and J. M. Kang, "Power management strategy for a parallel hybrid electric truck," *IEEE Transactions on Control System Technology*, Vol.11, No.6, pp.839-849, 2003.

[2] Z. L. ZHAO, D. Q Liu, M. H Liu, J. Li, and Q. N. Wang, "Study on control strategy and simulation for parallel hybrid electric vehicle," *Chinese Journal of Mechanical Engineering*, Vol.41, No.12, pp.13-18, 2005.

[3] M. Knebusch, "2004 Toyota Prius," *Machine Design*, Vol.76, No.8, pp.111-116, 2004.

[4] H. D. Lee and S. K. Sul, "Diesel engine ripple torque minimization for parallel type hybrid electric vehicle," *Thirty-Second IAS Annual Meeting*, New Orleans, LA, USA, 1997: 942-946.

[5] F. Yang, K. Zheng, T. Shen, J. Kako, and S. Yoshida, "Coordinated nonlinear speed control approach for SI engine with alternator," *Proceedings of the IEEE*, Vol.95, No.4, pp. 796-805, 2007.

[6] M. Kazunari, I. Yoshiaki, and I. Yukio, "Design of the surge control method for the electric vehicle powertrain," *SAE Paper*, 2002, 2002-01-1935.

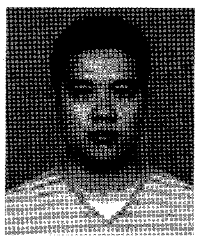
[7] I. D. Roy and D. L. Robert, "Engine torque ripple cancellation with an integrated starter alternator in a hybrid electric vehicle: implementation and control," *IEEE transaction on Industry Application*, Vol.39, No.6, pp.2016-2018, 2003.

[8] S. M. Cui, Y. Cheng, and C. C. Chan, "A basic study of electrical variable transmission and its application in hybrid electric vehicle." *Vehicle Power and Propulsion Conference (VPPC)*, 2006.

[9] M. J. Hoeijmakers and M. Rondel, "The electrically variable transmission in a city bus," *IEEE 35th Annual Power Electronics Specialists Conference*, Aachen, Germany, 2004: 2773- 2778.

[10] F. Wang, X. J. Mao, L. Yang, and B. Zhuo, "Control algorithm and parameter match for an electromagnetic coupling hybrid electric bus," *Journal of Xi'an Jiaotong University*, Vol.42, No.3, pp.342-346+358, 2008.

[11] Z. B. HE, H. B. BAI, P. L. ZHANG, and Q. C. Kong, "Engine dynamic characteristic and its effects on vehicular shift characteristics," *Journal of Ordnance Engineering College*, Vol.17, No.5, pp.17-20, 2005.



**Feng Wang**
He received his B.S. and M.S. degrees in School of Mechanical Engineering from Shanghai Jiaotong University, Shanghai, China in 2004 and 2006 respectively. He is currently a PhD candidate at Shanghai Jiaotong University. His current research interests include the optimal and coordinated control for hybrid electric vehicle.