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The Energy Management and Coordination in PHEV

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Abstract. The study object was the energy distribution in Parallel Hybrid Electric Vehicles (PHEV). The torque allocations both in static and dynamic state were discussed in details. Firstly, the torque allocations were concluded basing on the target torques. Then the dynamic coordination strategy was introduced according to the characteristics of different operating modes. Afterwards, co-simulation was founded using AVL/CRUISE and MATLAB/SIMULINK. At last, the outcomes indicate that the control strategies can achieve the expected goals.

Introduction

With the development of auto industry, the environment degradation and the scarce of fossil fuels contribute to the development restrictions in the traditional internal combustion engine vehicles (TEV) [1]. So researches of hybrid cars are becoming the hot topics currently [2]. The introduction of motors makes the engine working flexibly; however, it also brings the repulsion effect [3]. The coordination between motors and engines is the key of spread of PHEV [4]. The car also contains lots of nonlinear parts [5]. Dynamic coordination is needed to ensure the switching process to have a smooth transition. Thus the motor can coexist with the engine all the time to reduce the side effects.

Energy Management at Steady-state

Energy Allocations. The condition of the motor and the engine is determined according to the operating characteristics of engines and batteries.

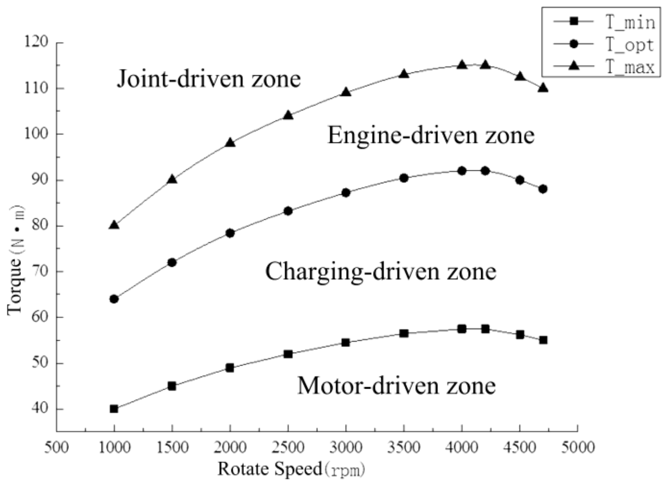

Fig.1 Working zones of the engine

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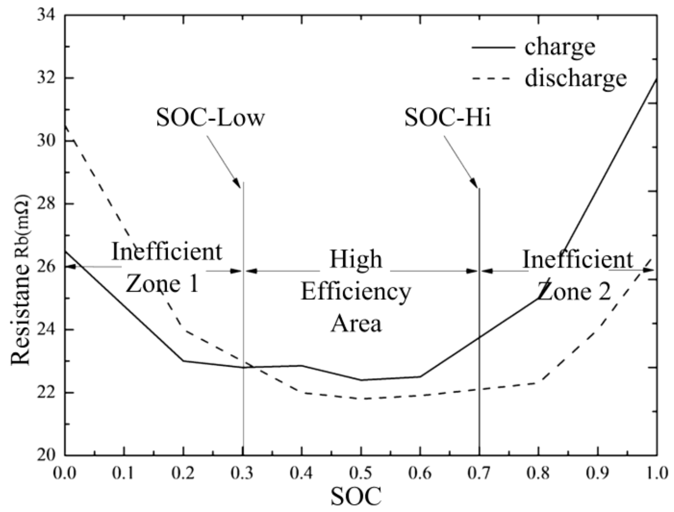

Fig.2 Working zones of the battery

Fig.1 shows the efficiency map of engines and it includes the engine performance curve $T_{e\_\max}$, the best working curve of engine T_{e_opt} and the minimum torque curve of engine T_{e_min}. According to the three mentioned curves, four work areas (joint-driven, engine-driven, charging-driven and motor-driven) are determined. Fig.2 shows the battery conditions that include SOC-Hi and SOC-low critical points. According to the two critical points, three work areas are concluded. If the state of the charge (SOC) is lower than SOC-low, it is in the first inefficient zone and it is better to be charged because of the low charge resistance. If SOC is higher than SOC-Low but not higher than SOC-Hi, it is in high efficiency area and it is possible to be charged and discharged because of the low charge and discharged resistance. If SOC is higher than SOC-Hi, it is in the second inefficient zone and it is better to be discharged because of the low discharged resistance. The working conditions are worked out and shown in Table 1.

Table 1 Working conditions of the battery in driven-process and braking-process

Working zone	Inefficient zone 1	Efficiency area	Inefficient zone 2
Joint-driven	Discharging	Discharging	Discharging
Engine-driven	Not work	Not work	Not work
Charging-driven	Charging	Charging	Not work
Motor-driven	Discharging	Discharging	Discharging
Braking	Charging	Charging	Not work

Torque Allocations in Motor and Engine. Target torque can be calculated with the help of the accelerator pedal stroke α and the brake pedal stroke β:

$$T_{driverdmd\_trq} = \alpha \times T_{drive\_trq\_max}. \tag{1}$$

$$T_{driverdmd\_trq} = \beta \times T_{brake\_trq\_max}. \tag{2}$$

Where: α、$\beta \in [0,1]$, $T_{drive\_trq\_max}$ and $T_{brake\_trq\_max}$ are the maximum target torques for accelerator pedal and brake pedal respectively.

The output of the torque coupler which connects motor and engine is target torque $T_{driverdmd\_trq}$. The equations are given as follows:

$$k_1 T_e + k_2 T_m = T_{driverdmd\_trq}. \tag{3}$$

$$\omega_t = \omega_e / k_1 = \omega_m / k_2. \tag{4}$$

Where: k_1 is the ratio of the number of gear teeth which links the motor to the number of gear teeth which links the transmission; k_2 is the ratio of the number of gear teeth which links the engine to the number of gear teeth which links the transmission; ω_m, ω_e and ω_t are the rotational speed of motor, engine and transmission input axis respectively; T_m and T_e are the output torque of motor clutch and engine clutch.

If the vehicle operates in joint-driven mode, the torque equations are given as follows:

$$T_e = T_{e\text{-}max}\,. \tag{5}$$

$$T_m = \left\{ \min\left(T_{driverdmd\_trq} - k_1 T \right) / k_2, T_{m\_pro\_max} \right\}. \tag{6}$$

If the vehicle operates in engine-driven mode, the torque equations are given as follows:

$$T_e = T_{driverdmd\_trq} / k\,. \tag{7}$$

$$T_m = 0\,. \tag{8}$$

If the vehicle operates in motor-driven mode, the torque equations are given as follows:

$$T_e = 0\,. \tag{9}$$

$$T_m = \min\left\{ T_{driverdmd\_trq} / k_2, T_{m\_pro\_max} \right\}. \tag{10}$$

If the battery are not allowed to be charged and the vehicle operates in charging-driven mode, the equation is the same as Eq.7 and Eq.8; If the battery are allowed to be charged and the vehicle operates in charging-driven mode, the torque equations are given as follows:

$$T_e = T_{e\text{-}opt}\,. \tag{11}$$

$$T_m = \max\left\{ \left(T_{driverdmd\_trq} - k_1 T \right) / k_2, T_{m\_reg\_max} \right\}. \tag{12}$$

The brake torque of driving wheel is the sum of motor regenerative braking torque and hydraulic torque. If the target torque is not higher than the maximum regenerative braking torque $T_{m\_reg\_max}$, the equation is shown in Eq.13; If the target torque is higher than the maximum regenerative braking torque, he equation is shown in Eq.14.

$$\begin{cases} T_e = 0 \\ T_m = T_{brakedmd\_trq} \end{cases}. \tag{13}$$

$$\begin{cases} T_e = 0 \\ T_m = T_{m\_reg\_max} \\ T_{b\_mach} = T_{brakedmd\_trq} - T_{m\_reg\_max} \end{cases}. \tag{14}$$

Where: T_{b_mach} is the hydraulic available torques.

Dynamic Coordination. Not all the modes have the direct switch to another one. The switches need to follow some fixed rules.Fig.3 shows that the rules can be classified into three types: switches among drive patterns, switches among brake patterns and switches between drive patterns and brake patterns. In terms of the drive patterns, clutch combination as well as the motor torque compensation should be paid more attention when the motor-driven pattern switches to other ones and the rate of change of output torque of the motor and the engine should be focused more when an engine participation pattern switches to another one. For the brake patterns, the lag of hydraulic braking and the compensation of regenerative braking should be mainly considered. For the switches between drive patterns and brake patterns, the clutch state should be taken into consideration.

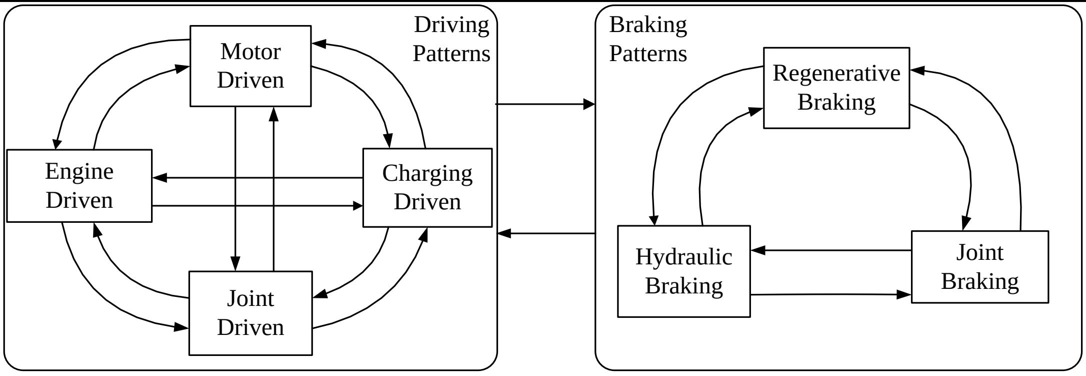

Fig.3 Rules of switches between different patterns

Fig.4 shows the dynamic control strategy. The CPU monitors whether there is a pattern switch all the time. If yes, the value of SWITCH_FLAG in the flow chart would become 1 and the CPU would judge whether there are intermediate links. The intermediate links have higher priorities. During this process, the advantages of response speed of the motor would compensate the problems of lacking torque caused by the lag of engine response; thereby ensuring a smooth switch. This compensation process would continue until the engine reaches the steady state. The value of SWITCH_FLAG would become 0 again when the procedure finishes.

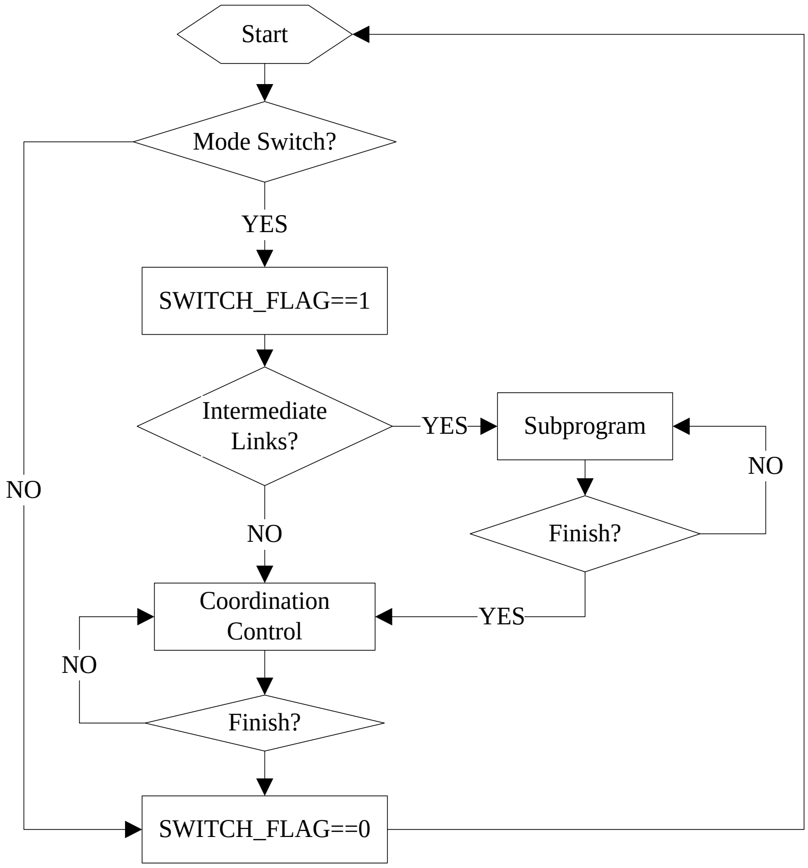

Fig.4 Dynamic control strategy

Model of Energy Management and Coordination

The model is established on the basis of MATLAB/SIMULINK platform with the software of AVL/CRUISE and co-simulation is applied.

Model of Data Collection. During the model of MATLAB API, braking signal comes from the comparison between maximum brake pressure and the brake pressure, the output of Cockpit. Shifting Flag, the shift signal of transmission, is determined by the logical comparison between

Desired Gear and Current Gear from CRUISE. The current velocity, engine rotate speed, motor rotate speed, transmission position, SOC of batteries, the actual state of clutch, accelerator pedal stroke, engine torque and motor torque also come from the real-time signals in CRUISE. Fig.5 shows this model.

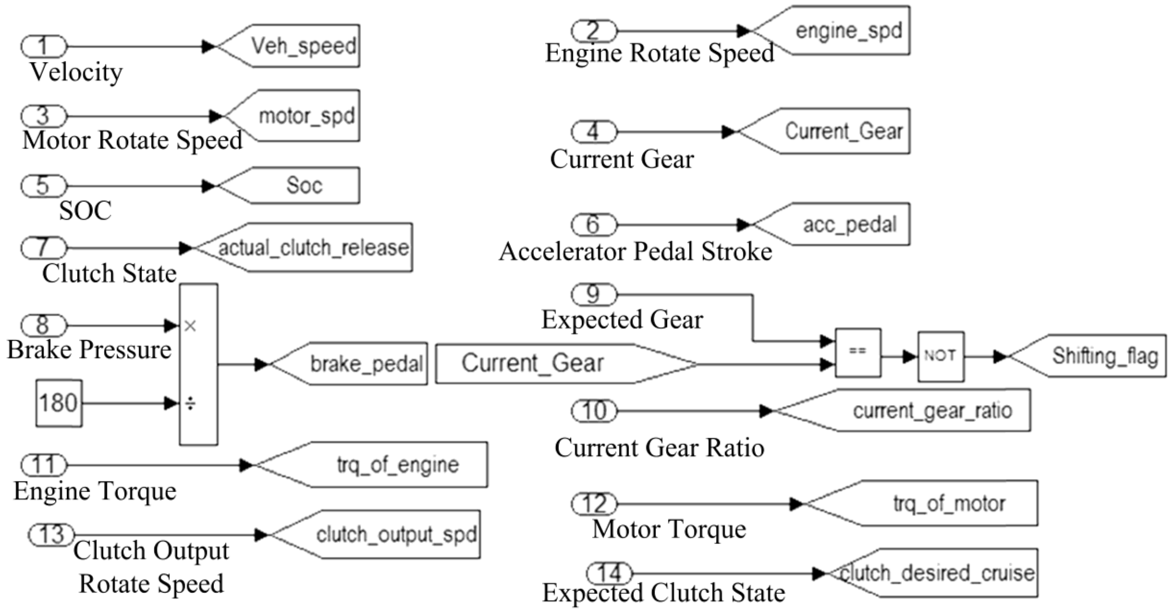

Fig.5 Model of data collection

Model of Target Torque. Fig.6 shows the model of target torque. The rotate speed of clutch needs to be checked whether it is lower than the engine idle. If so, the clutch is separated. The instant maximum torque is the sum of the instant maximum engine torque and the instant maximum motor torque. The torque of certain pedal stroke can be calculated according to the proportion.

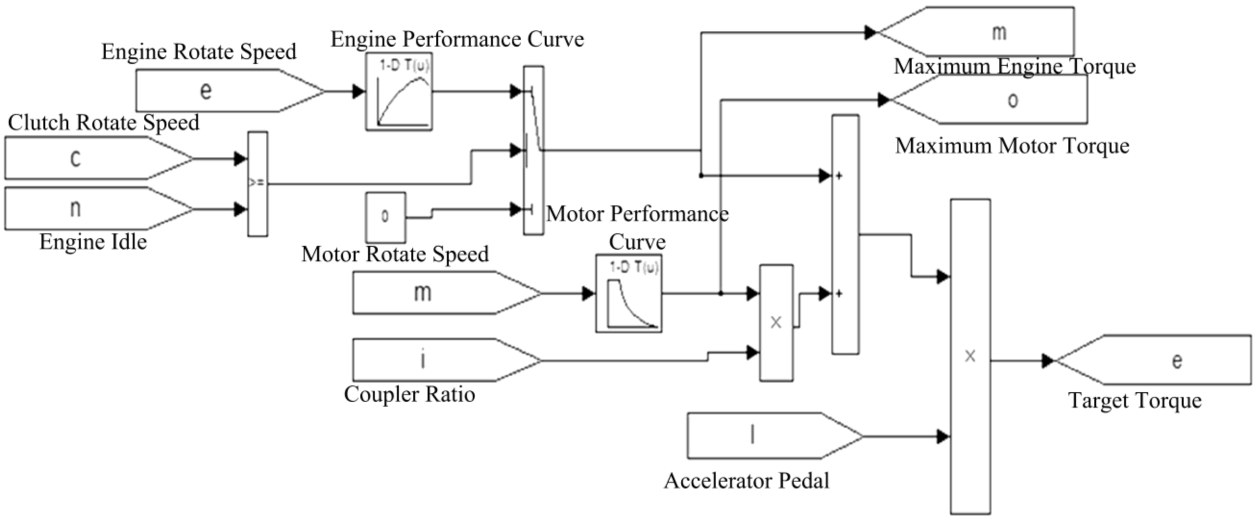

Fig.6 Model of target torque

Model of Torque Distribution. Fig.7 shows the model of torque distribution and the medel uses the threshold control strategy. The torque distribution model uses the threshold control strategy. The torque share of motor and engine are determined by the states of the batteries and the engine.

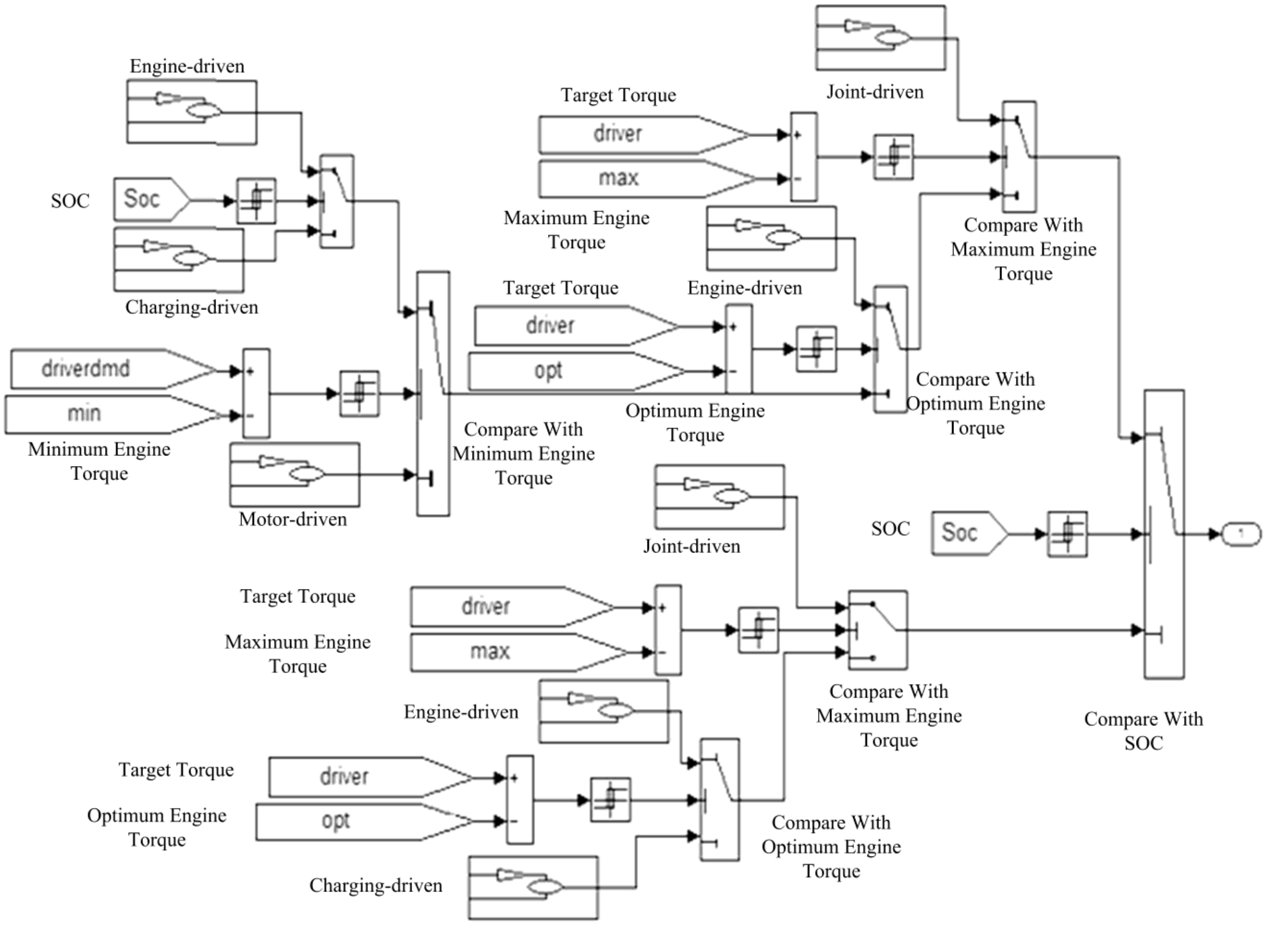

Fig.7 Model of torque distribution

Model of Dynamic Coordination. The dynamic coordination strategy is higher in priority than the torque distribution strategy. Fig.8 shows the model of dynamic coordination strategy. If a switch happens, the ECU would choose the corresponding strategy. This coordination process would continue until the transition finishes.

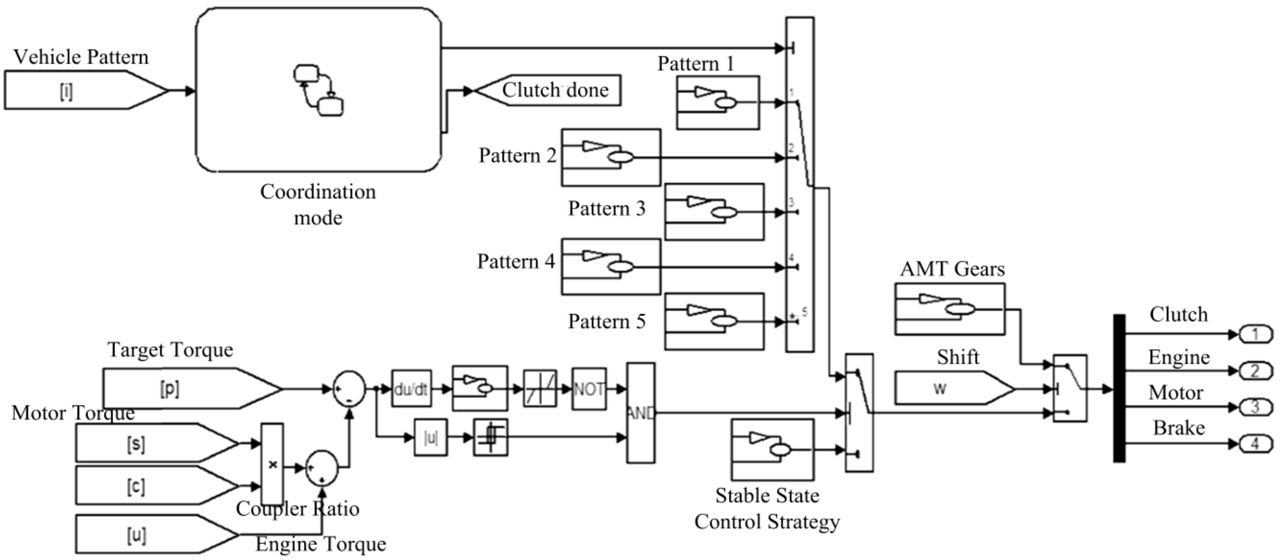

Fig.8 Model of dynamic coordination

Analyses of Simulation Results

The whole model, embedded in a PHEV, is simulated under the NEDC condition which includes urban conditions and suburban conditions.

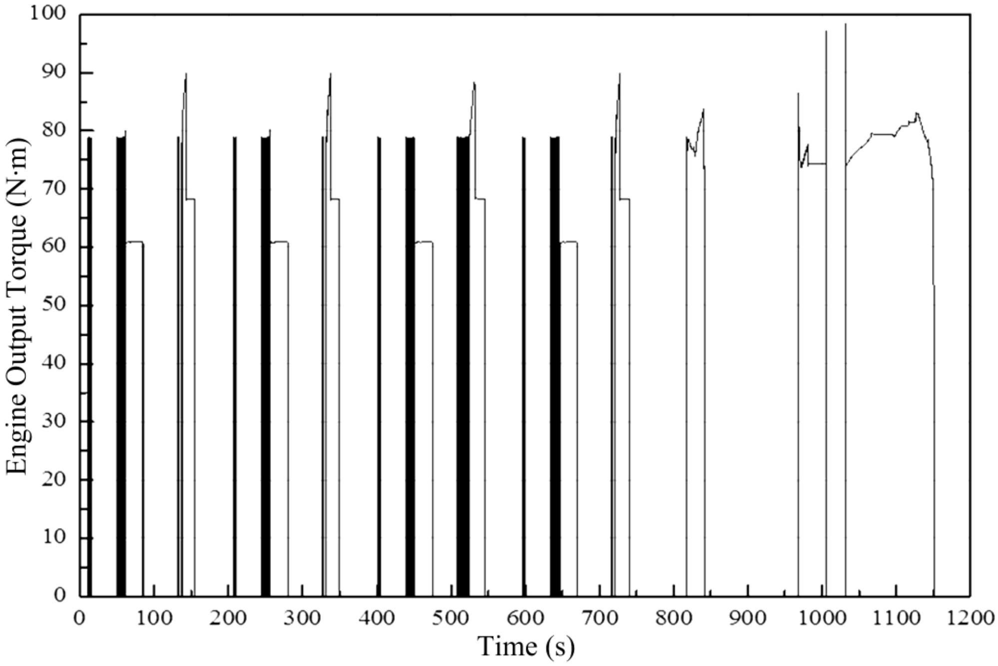

Fig.9 Engine output torques

Fig.9 shows the output torque of the engine during the whole period. It can be found that the output torques were relatively stable which means that the engine was working in fuel economic zone. So it can be concluded that the torque distribution is reasonable. In addition, the output torques during the transition period varied in a small scale which means that the engine had a smooth transition. So the dynamic coordination strategy is feasible.

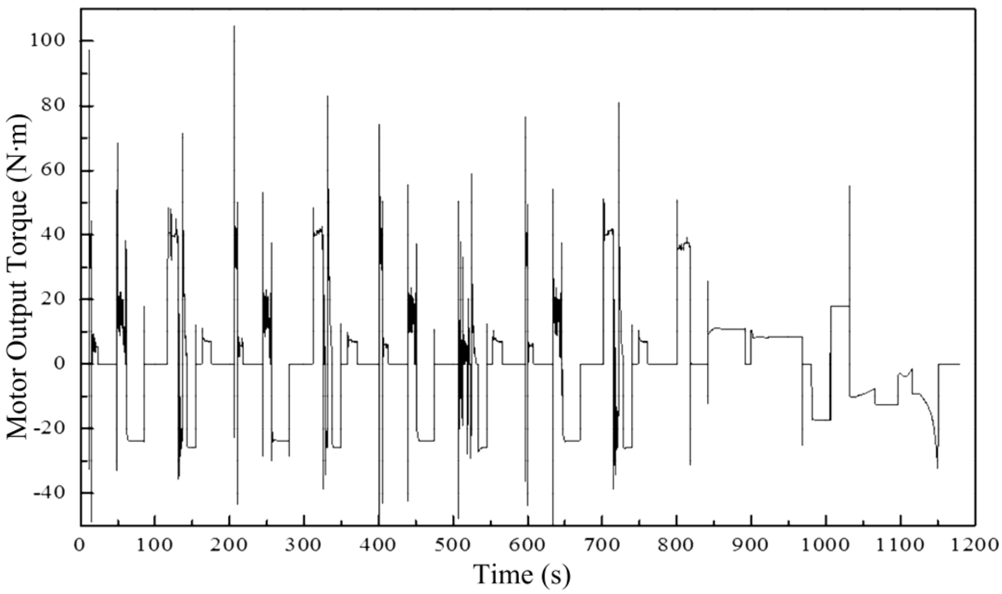

Fig.10 Motor output torques

Fig.10 shows the output torque of the motor. It is shown that the output torque was stable when the vehicle speed was steady which proves the validity of the torque distribution. However, the output torque suffered relatively large fluctuation. This is because that the motor was compensating the torque scarce at that time taking the advantages of rapid response speed of motors. In addition, the figure also shows that sometimes the motor provided the negative torque. It means that the motor was working at the regenerative braking pattern.

Table 2 indicates the performance with different controls in the same vehicle under the NEDC condition. It shows that the fuel consumption of PHEV using the torque distribution strategy is only 4.84L, 28.08% less than that of 6.73L in traditional internal combustion engine vehicle. So the torque distribution strategy can help the PHEV improve the fuel economy. It also shows that the fuel consumption of the same PHEV added the dynamic coordination strategy is 4.75L, 29.42% less than 6.73L and 1.86% less than 4.84L. So the dynamic coordination strategy can also help improve the fuel economy with a certain extent. Besides, the other data in the table shows that both the two strategies can help improve the fuel economy and reduce the emissions.

Table 2 Fuel consumption and emissions

Item	Traditional engine vehicle	PHEV with static strategy	PHEV with dynamic strategy
Fuel consumption [L/100km]	6.73	4.84	4.75
Time [s]	13540	13540	13540
The total fuel consumption [kg]	1.0772	0.3838	0.3556
Idling fuel consumption [kg]	0.1031	0.0023	0.0023
Acceleration fuel consumption [kg]	0.2015	0.1762	0.1614
Constant speed fuel consumption [kg]	0.6676	0.1567	0.1457
Reducing fuel consumption [kg]	0.1050	0.0485	0.0462
NO emission [g]	27.65	13.84	13.28
CO emission [g]	74.77	39.40	37.90
HC emission [g]	8.56	4.69	4.51

Summary

The torque distribution and the dynamic coordination strategies in PHEV were discussed. The results indicate that the torque distribution can make the engine in the PHEV always working in the fuel economic zone; thereby improving the fuel economy and reducing the emissions. They also show that the dynamic coordination strategy optimizes the processes of transitions between working patterns in order to make further efforts in improving the fuel economy.

Acknowledgements

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References

[1] Yerkes, J. W. "Electric vehicle developments in Europe and Japan."*Northcon/94 Conference Record*. IEEE, 1994.

[2] Shen, Zhong-Jie, et al. "Electric Vehicle: The Hope of the Green Future."*Management and Service Science (MASS), 2011 International Conference on*. IEEE, 2011.

[3] Chuanwei, Zhang, et al. "Study on regenerative braking of electric vehicle."*Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International*. Vol. 2. IEEE, 2004.

[4] Sciarretta, Antonio, Michael Back, and Lino Guzzella. "Optimal control of parallel hybrid electric vehicles." *Control Systems Technology, IEEE Transactions on* 12.3 (2004): 352-363.

[5] Sciarretta, Antonio, and Lino Guzzella. "Control of hybrid electric vehicles."*Control systems, IEEE* 27.2 (2007): 60-70.