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Electromechanical Components and its Energy Saving Design Strategy in PHEV Powertrain

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Abstract

This paper presents advanced Compact Hybrid Planetary Transmission Drive (CHPTD) as a solution for the plug-in hybrid electric vehicle (PHEV). Proper architecture and elements were designed to achieve the functions of PHEV. The parameters of powertrain were adjusted and optimized by simulation. Two basic control strategies were selected and analyzed to achieve minimum energy consumption and the proper operation range of battery state of charge (SOC). The very effective operation of the improved powertrain was proved by tests in different driving cycles regarding the traffic both in city and suburb area. The advantage of planetary transmission, which is power summing mechanical unit, was obtained by the proper design and the control of innovative high energy saving electromagnetic clutch-brake device based on classic dual-diaphragm spring system, which also permits to apply multi-speed additional automatic mechanical transmission.

Keywords: PHEV (plug in hybrid electric vehicle), powertrain, planetary gear, optimization

1 The plug-in hybrid powertrain based on CHPTD and clutch-brake system

1.1 The configuration of powertrain

As a member of hybrid electric vehicles, the plug-in hybrid plays an affirmative role in both academic and industrial areas. From the topologic point of view, plug-in hybrids are based on the same powertrain as conventional hybrid vehicles. However, the proper adjustment of vehicle parameters is necessary to fulfill the functionality requirements of plug-in hybrid.

As well known, high power electric motor, automatic transmission (AMT) and dual clutch are very expensive components. In Toyota hybrid system, all above mentioned components are employed. There are more clutches and gearbox equipped in the advanced Compact Hybrid Planetary Transmission Drive (CHPTD), but all the clutches and clutch-brake system are designed with existing friction clutch components, which means the cost is low. The 4-speed gearbox includes only several sets of gears and 2 clutches which could be more cost efficient than other existing AMT. In Toyota and classical series-parallel hybrid system, the pure engine operating mode is not available. But in CHPTD, all operating modes, which are pure electric start, pure engine drive, hybrid drive and regenerative brake, are available. This is a big advantage of CHPTD.

The original CHPTD is a complex hybrid powertrain architecture which was originally invented and developed by Prof. Szumanowski [1].

In this paper, the plug-in hybrid powertrain design was based on the original CHPTD. Figure 1 shows the new CHPTD with an additional gearbox.

The CHPTD is a low cost solution for it uses only one set of planetary gears and one electric motor for all operating modes. A small internal combustion engine (1.2L gasoline) is employed as an alternative power source. As a power summing unit, the planetary gearbox combines two power sources and the output shaft. CHPTD could achieve higher efficiency than other existing hybrid powertrain because of its efficient power distribution via planetary transmission [2]-[6].

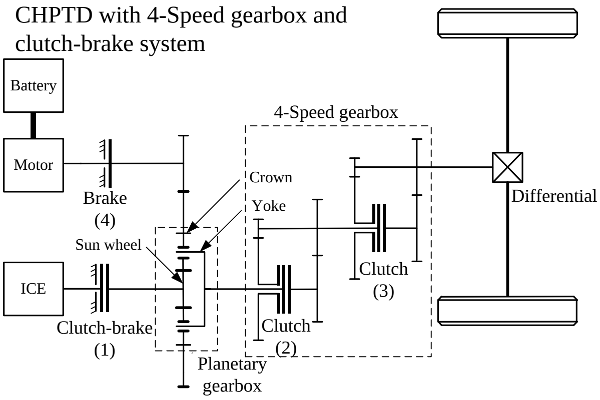


Figure1: The configurations of new CHPTD with gearbox (See construction of clutch-brake systems in Figure 5)

Several sets of clutch-brake system are used together with mechanical transmission for changing operating modes of the powertrain and adjusting gear ratio. It provides the possibility and flexibility for advanced control strategies of the CHPTD.

A 4-speed gearbox is necessary for adjusting the operating area of ICE and electric motor in different speed range of the vehicle, which means improving the energy efficiency. With a properly shifting gearbox, the efficiency of regenerative braking can be improved as well.

1.2 The clutch-brake system

The clutch-brake system employed in the CHPTD influences on the performance of the whole system. However, the existing electromagnetic clutch-brake system consumes electric power continuously. To minimize the energy consumption, the innovative zero steady-states electrical energy consumption clutch-brake system is selected [7]. As a low cost solution, dry friction clutch is considered as the foundation of the new clutch design. The majority elements in this clutch-brake system, such as diaphragm spring, friction plate, bearing, are available from existing dry friction clutch. Using these elements, authors designed a new configuration of clutch-brake system (see Figure 2). The Dual diaphragm spring and the actuation system are key points of the design.

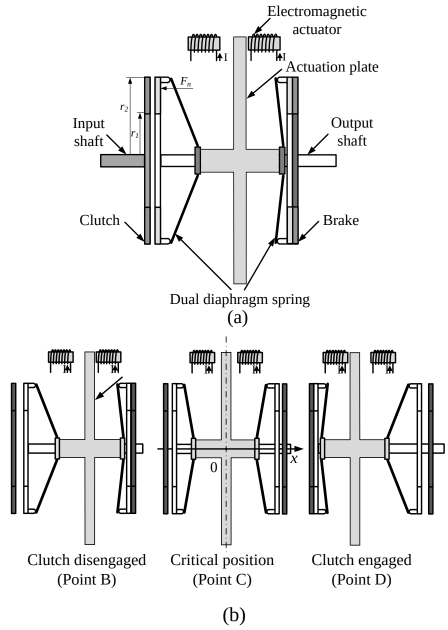


Figure2: (a) the configuration of the innovative zero steady-states electrical energy consumption clutch-brake system; (b) operating position of clutch according to Point B, C, D in Figure 3c respectively (Point C is a transient state)

The dual diaphragm spring is a key element in the design. Figure 3b is the characteristic of a single diaphragm spring. By connecting two diaphragm springs in opposite direction and setting the initial position of both diaphragms to point O on their characteristic curves, the characteristic of dual diaphragm spring is obtained as shown in Figure 3c.

The dual diaphragm spring has two steady-states, which are engagement and disengagement of the clutch (see Figure 2b). In the operation of the clutch, the dual diaphragm spring works between point B and D of its characteristic curve (see Figure 3c).

Two sets of electromagnetic actuator are necessary to create actuation force in opposite directions. During engaging, dual diaphragm spring moves from point B to point D. According to the characteristic of dual diaphragm spring, the actuation force only applies on the actuation plate when the dual diaphragm spring moves from point B to point C. The clutch can engage automatically after the spring crosses the critical point C. And the energy consumption during the steady state is zero. For disengaging, the dual diaphragm spring works in an opposite direction of engaging.

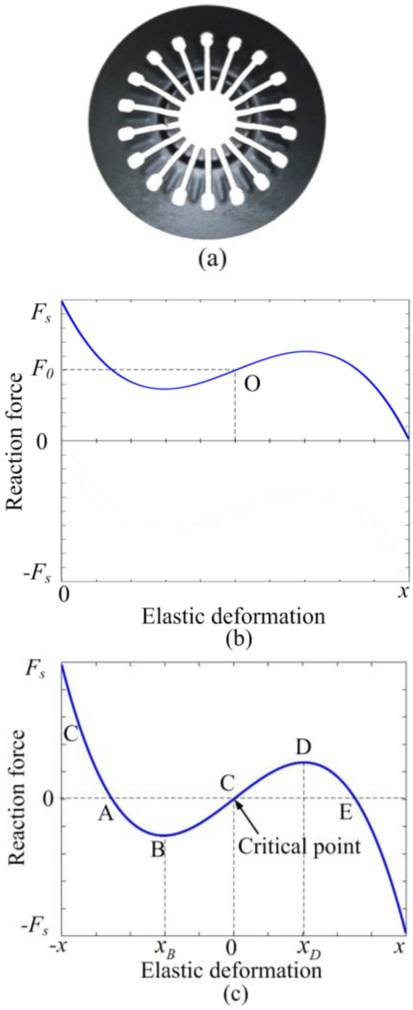


Figure3: (a)Diaphragm spring; (b)The characteristic of single diaphragm spring; (c)The characteristic of dual diaphragm spring

Figure 4 presents the construction of clutch-brake system for different applications, which consist of clutch-brake, dual-clutch and brake. By activating different sets of electromagnet coil, it can change the states of clutch-brake system. Based on aforesaid concept, a clutch with improved actuation solution is designed (see Figure 5). An additional bearing is employed to keep the actuation plate working in non-rotary condition. 2 sets of solenoids are used as electromagnetic actuators. This design is dedicated to dual-clutch application. However, with small adjustment, this design could also be used for clutch-brake or only brake applications. Compared with the rotary actuation solution, this design features lower abrasion and more stability.

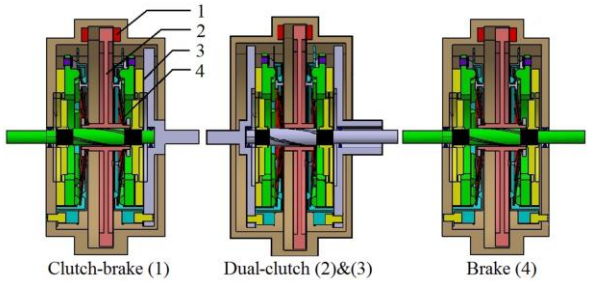


Figure 4: Zero steady-states electrical energy consumption clutch-brake systems for different applications
1-Electromagnetic actuator 2-Actuation plate
3-Friction plate 4-Diaphragm spring

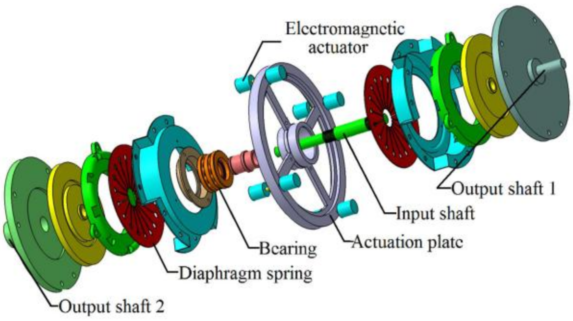


Figure 5: Assembly of zero steady-states electrical energy consumption clutch with solenoid actuation for dual clutch application

2 Simulation and the parameters optimization of CHPTD

2.1 Simulation parameters

To evaluate the feasibility of the concept and to optimize the parameters of CHPTD, a dynamic model of the plug-in hybrid powertrain was built in MATLAB/SIMULINK environment by using the mathematical models of different components. [8]-[11] An ultra-light basket-tube frame vehicle is considered as the basic vehicle model in simulation (see Figure 6). In order to analyze the influence of different control strategies and parameters, different comparison simulations were done under NEDC (New European Driving Cycle).Table 1 shows the parameters of the vehicle and the CHPTD. The parameters are properly adjusted by analyzing the requirements and verified by simulation.

Figure 6: The ultra-light basket-tube frame vehicle designed and prototyped by Prof. Szumanowski's team

Table 1: Simulation parameters of vehicle and its main components

Vehicle	
Vehicle mass [kg]	750
Rolling resistance coefficient	0.008
Aerodynamic drag coefficient	0.33
Front surface square [m^2]	1.6
Dynamic radius of wheel [m]	0.257
Driving cycle	NEDC
Main reducer ratio	3.62
Battery	
Battery type	Li-ion
Battery pack number	3
Nominal voltage [V]	43*3
Nominal capacity [Ah]	30
PM motor*(Unique Mobility)	
Nominal voltage	195VDC
Peak power [kW]	32
Continuous power [kW]	16
Maximal rotary speed [rpm]	4000
Nominal torque [Nm]	40
ICE (Gasoline)	
Displacement	1.2L
Maximal power [kW]	35 (at 4500 rpm)
Maximal torque [Nm]	78 (at 5000 rpm)
Rotary speed rang [rpm]	1000~5000

* The PM motor control system is based on buck-boost convertor (voltage up for motoring, voltage down for generating) connected with battery. There is also 3-phase PWM inverter between buck-boost converter and PM motor.

2.2 The Control strategy

The control strategy of powertrain is connected with the clutch-brake operation. The relation between control signal of clutch-brake system and operating modes of CHPTD is shown in Table 2.

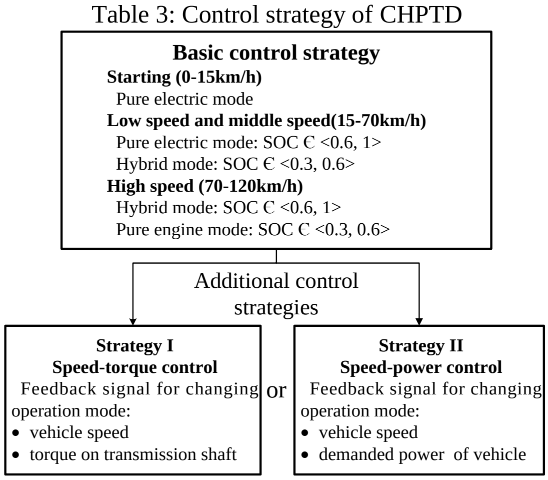
Table 2: Control signal of clutch-brake system for different operating modes of CHPTD (see Figure 1)

Operating mode of CHPTD	**Control signal of clutch-brake system**	
	Clutch-brake (1)*	**Brake (4) ****
Pure electric and regenerative braking	off	off
Pure engine	on	on
Hybrid	on	off
Engine charge battery (when vehicle stop)	off	off

* 'On': clutch engaged and brake disable; 'off': clutch disengaged and brake enable.
** 'On': brake enable; 'off': brake disable.

The full control strategy is divided into basic parts and additional parts (see Table 3). In basic control strategy, vehicle speed and battery SOC are used as feedback signals to change the operating mode of CHPTD. In order to achieve lower fuel consumption and the function of plug-in hybrid, two additional control strategies are designed for comparison. Separately, the torque on transmission shaft and demanded power of the vehicle influences changing operating modes for low speed drive.

Table 3: Control strategy of CHPTD



Furthermore, an additional threshold of battery SOC is set to determine operating mode of hybrid powertrain. When battery SOC is higher than threshold, pure electric mode is enabled for low and middle speed drive. It means that more electric energy is consumed to limit the emission. When battery SOC is lower than threshold, pure electric mode is only enable for starting, which means the powertrain works just like conventional HEV.

To investigate influences of different control strategies, comparison simulation was made. Figure 7 and Table 4 show the simulation results with different control strategies under the same condition. With Strategy II, battery SOC is limited to the proper set value 0.5 at the end of simulation, while battery SOC is out of control and decreases to 0.18 in Strategy I. Although fuel consumption with Strategy I is 2% less than that with Strategy II for the same driving range, the powertrain could work in hybrid mode for longer distance with Strategy II to achieve better emission performance with proper control of battery operating range. Considering requirements of plug-in hybrid and similar fuel economy performance, Strategy II is better than Strategy I. The simulation in the ensuing study is based on Strategy II.

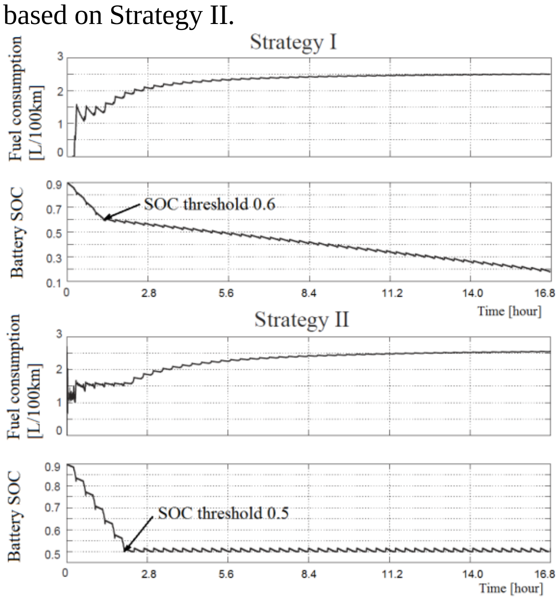


Figure 7: Simulation results with different control strategies in 50 NEDC cycles

Table 4: Simulation results with different control strategies in 50 NEDC cycles

	Strategy I	Strategy II
Total driving range[km]	540	540
Total fuel consumption[L]	13.55	13.82
Average fuel consumption [L/100km]	2.51	2.56
SOC at the end of simulation	0.18	0.52

2.3 Simulation for pure electric drive

Battery capacity influences on driving range for pure electric drive of plug-in hybrid powertrain. To fulfill the functionality of plug-in hybrid, battery capacity is adjusted to 3.9kWh.

In urban area of most European cities, the speed limitation is 50~60km/h. The pure electric drive of designed vehicle is most considered in urban driving. NEDC driving cycle with limited top speed 65km/h (with a small margin) is used in the simulation. According to the simulation results, it can achieve 55km driving range during pure electric operating mode with battery SOC alteration from 0.95 to 0.4 by applying optimized shifting schedule of gearbox.

2.4 Gear ratio optimization

According to the configuration of CHPTD (Figure 1), several sets of gears are equipped, which are as below:

- Planetary gear
- Additional reducer between ICE and planetary gear
- Additional reducer between electric motor and planetary gear
- 4-speed gearbox

The ratio of all these gears has an influence on the performance of power distribution and operating area of ICE and electric motor.

The target of gear ratios optimization is to minimize the internal loss and the energy consumption, which consists of fuel consumption and electric motor efficiency.

Basic ratio of planetary gear

Basic ratio of planetary gear influences on the power distribution of hybrid powertrain. The simulation results in Table 5 show that lower basic ratio of planetary gear could achieve better fuel economy performance. The basic ratio of planetary may not be a specific number because of the limitation of manufacturing, dimension and other practical reason. The ratio in Table 5 is properly selected by fulfilling these requirements.

Table 5: Simulation results for different basic ratio of planetary gear (Other gear ratio is assumed to be stable*)

Basic ratio of planetary gear	Average fuel consumption [L/100km]	Average efficiency of motor [%]
1.80	2.186	76.95
1.875	2.201	76.32
1.99	2.218	75.97
2.25	2.260	75.09
2.99	2.383	73.56

*1st gear ratio: 2.00; 2nd gear ratio: 1.50; 3rd gear ratio: 0.95; 4th gear ratio: 0.83; ICE reducer ratio: 3.22; Electric motor reducer ratio: 1.98

** Simulation time: 30000s; driving range: 270km; batter state of charge alteration: 0.9 to 0.5

The ICE reducer ratio and electric motor reducer ratio are optimized with similar approach.

Gear ratio of 4-speed gearbox

The 4-speed gearbox is an important element for the plug-in hybrid powertrain. With properly adjusted gear ratios and gear shifting schedule, it could increase the energy efficiency under different driving conditions. Considering both the dynamic performance and the fuel economy, the gear shifting schedule is as blow.

- 1st-gear: 0~15km/h
- 2nd-gear: 15~40km/h
- 3rd-gear: 40~70km/h
- 4th-gear: 70~120km/h (or higher speed)

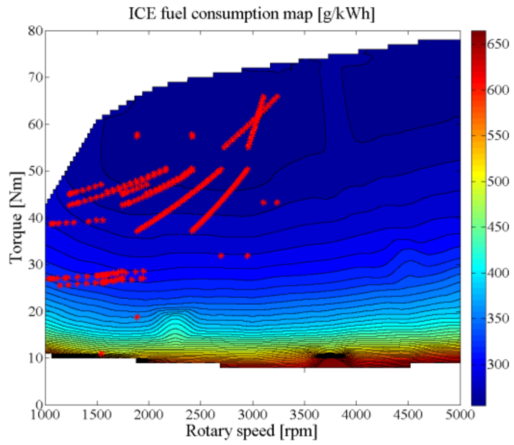
Table 6: Simulation results for different gear ratio of 4-speed gearbox (Other gear ratio is assumed to be stable)*

No.	1st gear	2nd gear	3rd gear	4th gear	Average fuel consumption [L/100km]	Average efficiency of motor [%]
1	2.00	1.50	1.10	0.90	2.301	75.40
2	2.00	1.50	1.00	0.90	2.259	75.95
3	2.00	1.50	1.00	0.90	2.251	76.25
4	2.00	1.50	1.10	0.83	2.227	76.21
5	2.00	1.60	0.95	0.83	2.213	75.99
6	2.00	1.50	1.00	0.83	2.206	76.36
7	2.00	1.50	0.95	0.85	2.199	76.73
8	2.50	1.50	0.95	0.83	2.192	76.42
9	2.20	1.50	0.95	0.83	2.189	76.58
10	2.00	1.50	0.95	0.83	2.186	76.69
11	2.00	1.45	0.95	0.83	2.176	76.95
12	1.20	1.20	1.20	1.20	2.567	74.90

* Basic ratio of planetary gear: 1.80; ICE reducer ratio: 3.22; Electric motor reducer ratio: 1.98
** Simulation time: 30000s; driving range: 270km; batter state of charge alteration: 0.9 to 0.5

Table 5 and 6 show the trend that gear ratios influence the fuel consumption and the efficiency of the motor. In selected range, the best ratios are indicated by highlight in Table 5 and 6. However, the real gear ratio optimization is more complicated because changing one gear ratio is connected with the change of others. The adjustment of gear ratio should cooperate with the operating area of ICE and electric motor, because gear ratio optimization is also limited by practical performance and other binding conditions. For example, the operating points of ICE and electric motor should locate in limited range, and the proper power of electric motor should be reserved for acceleration and grade ability.

The simulation results in Table 6 also show the necessity of a 4-speed gearbox. By equipping 4-speed gearbox, the average fuel consumption decreases 16.3% compared with that without a gearbox (see data No. 11 and 12 in Table 6). Figure 8 and 9 present operating points of ICE and electric motor with and without 4-speed gearbox transmission.



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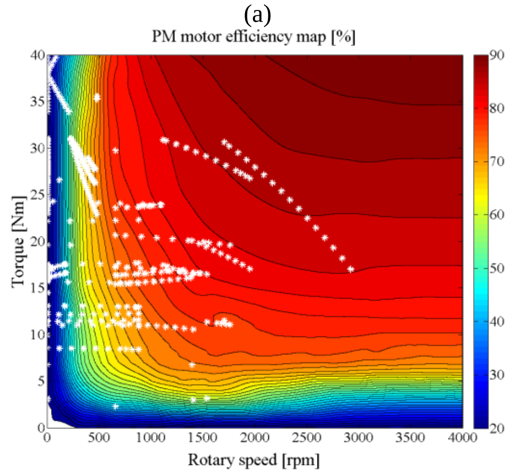
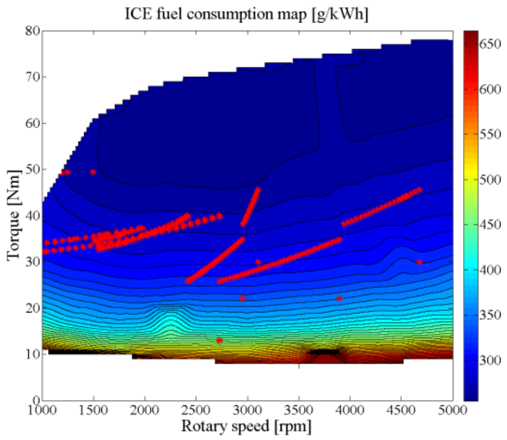


(b)

Figure 8: (a) Operating points of ICE with 4-speed gearbox transmission; (b) operating points of electric motor with 4-speed gearbox transmission (according to data No. 11 in Table 6)



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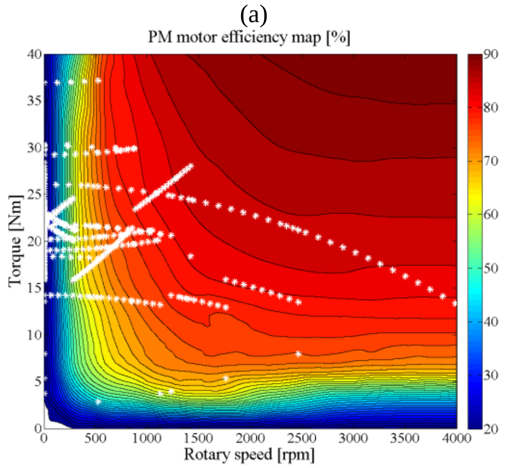


(b)

Figure 9: (a) Operating points of ICE without 4-speed gearbox transmission; (b) operating points of electric motor without 4-speed gearbox transmission (according to data No. 12 in Table 6)

According to operating points of ICE in Figure 10a, the selected ICE has more power than demanded. It means a smaller ICE should be selected for such a light vehicle. It also presents that simulation is an effective method to correct and verify the design.

Figure 10 presents the simulation results of two driving cycles in different battery state of charge conditions.

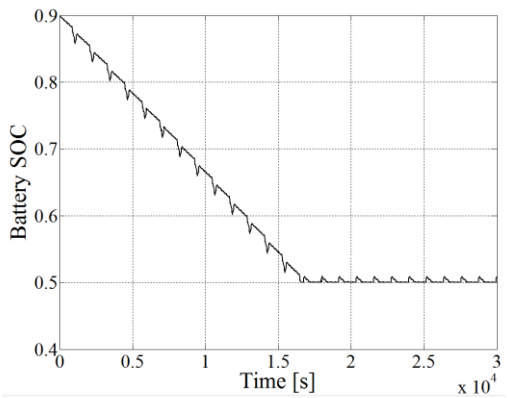
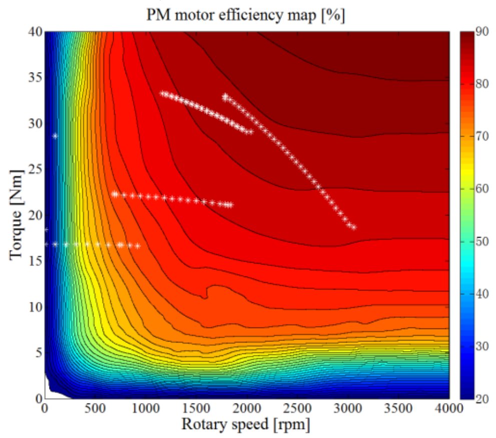


Figure 10: Battery SOC alteration in simulation according to data No. 11 in Table 6

2.5 Energy efficiency of regenerative braking

When the plug-in hybrid powertrain works in regenerative braking mode, the equivalent torque on the electric motor shaft influences energy efficiency. With proper control of a 4-speed gearbox, it could change the operating points of the electric motor to increase the energy efficiency during regenerative braking. The energy efficiency of regenerative braking is regarding to kinetic energy of vehicle and regenerated electric energy stored in battery.

Comparison exemplary simulation was carried out to analyze energy efficiency of regenerative braking with and without gearbox for 750kg vehicle. According to simulation results, average efficiency of regenerative braking increases form 67.16% to 76.01% in NEDC driving cycle. Figure 11 shows the operating points of electric motor during regenerative braking from 120km/h to 0km/h within 35s.



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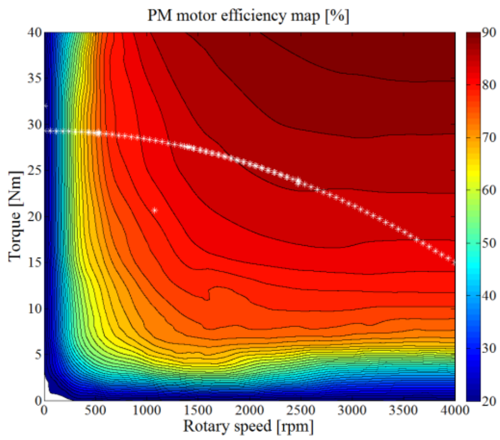

(b)

Figure 11: (a) Operating points of electric motor with 4-speed gearbox transmission during regenerative braking (simulation data according to Table 6 No. 11); (b) operating points of electric motor without gearbox transmission during regenerative braking (simulation data according to Table 6 No. 12)

3 Conclusions

This paper presents the method of designing the plug-in hybrid powertrain with planetary transmission. The simulation results which are based on simulation in MATLAB/SIMULINK environment show that:

CHPTD is a suitable configuration for plug-in hybrid application. The advantage of planetary transmission is obtained by proper design and control of a new electromagnetic clutch-brake system.

Control strategy influences the performance of hybrid powertrain significantly. With the proper control strategy, the plug-in hybrid powertrain could achieve good performance on fuel consumption and battery SOC management.

With optimized gear ratio and control strategy, the implementation of 4-speed gearbox increases the fuel efficiency in different driving conditions. According to the simulation results, the fuel consumption of hybrid powertrain with 4-speed gearbox is decreased by 14.8% compared to that without gearbox. Generally, with equipping 4-speed gearbox, it also increases energy efficiency of regenerative braking by 8.8%.

Anyway, additional speeds of gearbox can allow PHEV/EV to pass some steeps which would be not possible for constant ratio reducer applied if the maximal vehicle speed has to be the same.

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