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].

CHPTD with 4-Speed gearbox and clutch-brake system

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.

![Figure 2: (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)](image-url)
zero. For disengaging, the dual diaphragm spring works in an opposite direction of engaging.

Figure 3: (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.

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.
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 |
|------------------------------|---------------------------------------|
| Pure electric and            |                                       |
| regenerative braking         | Clutch-brake (1)*                     |
| Pure engine                  | Brake (4)**                           |
| Hybrid                       |                                       |
| Engine charge battery (when  |                                       |
| vehicle stop)                | 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

| Basic control strategy |
|------------------------|
| Starting (0-15km/h)    |
| Pure electric mode     |
| Low speed and middle-speed (15-70km/h) |
| Pure electric mode: SOC Ε 0.6, 1> |
| Hybrid mode: SOC Ε 0.3, 0.6> |
| High speed (70-120km/h) |
| Hybrid mode: SOC Ε 0.6, 1> |
| Pure engine mode: SOC Ε 0.3, 0.6> |

| Additional control strategies |
|--------------------------------|
| Strategy I                     |
| Speed-torque control           |
| Feedback signal for changing operation mode: |
| • vehicle speed                |
| • torque on transmission shaft |
| Strategy II                    |
| Speed-power control            |
| Feedback signal for changing operation mode: |
| • vehicle speed                |
| • demanded power of vehicle    |

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.

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 battery SOC is 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.

| Vehicle mass [kg] | 750 |
| Rolling resistance coefficient | 0.008 |
| Aerodynamic drag coefficient | 0.33 |
| Front surface square [m²] | 1.6 |
| Dynamic radius of wheel [m] | 0.257 |
| Driving cycle | NEDC |
| Main reducer ratio | 3.62 |
| Battery type | Li-ion |
| Battery pack number | 3 |
| Nominal voltage [V] | 43*3 |
| Nominal capacity [Ah] | 30 |
| Nominal voltage | 195VDC |
| Peak power [kW] | 32 |
| Continuous power [kW] | 16 |
| Maximal rotary speed [rpm] | 4000 |
| Nominal torque [Nm] | 40 |
| Displacement | 1.2L |
| Maximal power [kW] | 35 (at 4500 rpm) |
| Maximal torque [Nm] | 78 (at 5000 rpm) |
| Rotary speed range [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.
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.

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.

| 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

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.

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

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

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

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

![Figure 8](image_url)
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.

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.
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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