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Design of Planetary Plug-in Hybrid Powertrain and Its Control Strategy

Antoni Szumanowski[1], Zhiyin Liu[1], Yuhua Chang[1]

[1]*The Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, ul. Narbutta 84, Warsaw, 02-524, Poland*
E-mail: Antoni.Szumanowski@simr.pw.edu.pl, zliu@simr.pw.edu.pl, yuhua.chang@simr.pw.edu.pl

Abstract

This paper presents the new compact hybrid planetary transmission drive (CHPTD) as a solution of plug-in hybrid electric vehicle (PHEV). The presented CHPTD is more compact and lower costs than other series-parallel hybrid drives equipped with planetary transmission and two motors. Proper architecture and elements were designed to achieve functions of PHEV. The powertrain and its components were optimized and determined by nonlinear dynamic modeling and simulations. Parameters of powertrain were adjusted and optimized by observation of simulation results. Two basic control strategies were analyzed to achieve minimum energy consumption and suitable operation range of battery state of charge. The very effective operation of the worked out powertrain was proved by tests in different driving conditions regarding city traffic and suburb area. The advantages of planetary transmission which is power summing mechanical unit, was obtained by proper design and control of innovative high energy saving electromagnetic clutch/brake device based on classic dual-diaphragm spring system.

Keywords— plug-in hybrid, planetary transmission, design, simulation, energy consumption minimizing

1 Configuration design of plug-in hybrid powertrain with planetary transmission

1.1 Configuration design

Different topologies of hybrid powertrain system have been developed in the past decades. Generally, plug-in hybrids are based on the same powertrain architectures as conventional electric hybrids.

The Compact Hybrid Planetary Transmission Drive (CHPTD) is a complex hybrid powertrain architecture which was original invented and developed by Prof. Szumanowski [1]. In this paper, CHPTD is applied as basic architecture in configuration design of plug-in hybrid powertrain.

Figure 1 shows the new CHPTD with proper adjustment for plug-in hybrid.

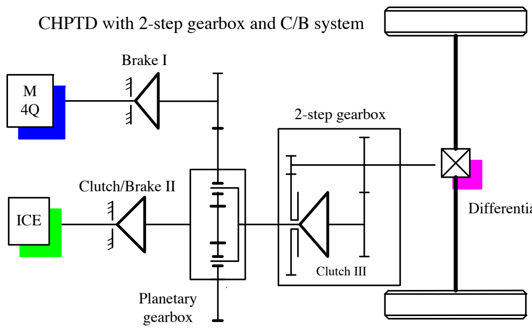

Fig. 1: Configuration of new CHPTD with proper adjustment for plug-in hybrid

CHPTD uses only one electric motor for all operating modes such as pure electric drive, hybrid drive and regenerative braking. A small internal combustion engine is employed as an alternative power source. As a power summing unit, the planetary gearbox combines two power sources.

Clutch/brake system is equipped in powertrain to achieve different operating modes of plug-in hybrid powertrain. When either Brake I or Clutch/Brake II works in braking status, the freedom degree of planetary gearbox decreases from 2 to 1. It gives more possibility and flexibility for advanced control strategies of plug-in hybrid powertrain.

Additionally, a 2-step gearbox is equipped to obtain better performance of energy consumption in different working conditions. It also extends the driving range of hybrid vehicle.

1.2 Clutch/brake system design

The clutch/brake system employed in the plug-in hybrid powertrain influences the performance of whole system. However, the existent 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 [2]. Figure 2 presents the clutch/brake system for different applications, which consists of brake, clutch/brake and clutch for three shafts.

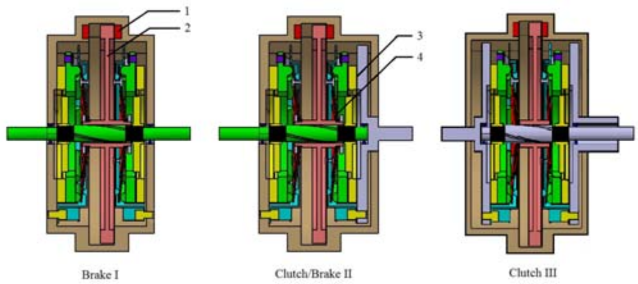

Fig. 2: Construction of zero steady-states electrical energy consumption clutch/brake systems

1- Electromagnetic actuator; 2 - Clutch release plate; 3 - Friction plate; 4 - diaphragm spring

By profiting from the nonlinear characteristic of dual-diaphragm spring, the clutch/brake system can keep steady-states without consuming any electric energy.

2 Modeling

In order to evaluate the feasibility of designed planetary plug-in hybrid powertrain and to optimize the parameters of system, dynamic model was built in MATLAB SIMULINK environment by using the original mathematical or digital models of each components.

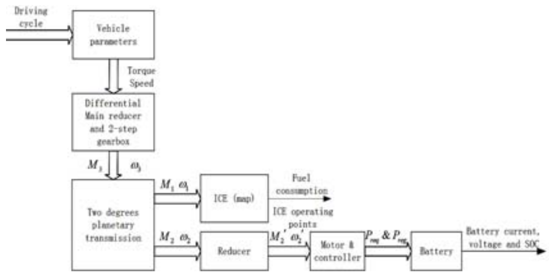

Fig. 3: The simulation flow of planetary plug-in hybrid powertrain dynamic model

2.1 Vehicle model

The mathematical equations used for vehicle model are as following. The gradient resistance F_g was ignored to simplify the model.

$$M_{wheel} = (F_f + F_{aero} + F_{acc} + F_g) r_{dyn} \tag{1}$$

$$F_f = mg\cos\alpha f \tag{2}$$

$$F_{aero} = \frac{c_x A}{21.15} v^2 \tag{3}$$

$$F_{acc} = \frac{1}{3.6} m\delta_b \frac{dv}{dt} (\delta_b = 1 + \frac{J_s j^2 \eta_m + \sum J_k}{m r_{dyn}^2}) \tag{4}$$

2.2 Planetary transmission model

Planetary gearbox combines power, torque and angular velocities of ICE, electric motor and output shaft. In this application, the ICE, electric motor and output shaft connect to sun wheel, crown and yoke of planetary gear separately. The following equations describe the relation of torque and angular velocity. In these equations, k_p is basic ratio of planetary gear which makes big influence on power summing and differencing of hybrid powertrain.

$$\omega_1 + k_p \omega_2 - (1 + k_p)\omega_3 = 0 \tag{5}$$

$$J_1 \dot{\omega}_1 = \eta_1 M_1 - \frac{1}{k_p} \eta_2 M_2 \tag{6}$$

$$J_3 \dot{\omega}_3 = M_3 + \frac{k_p + 1}{k_p} \eta_3 M_2 \tag{7}$$

2.3 ICE model

ICE model is based on engine map (Figure 4). By inputting torque and rotary speed of engine, fuel consumption rate is obtained as output of engine map.

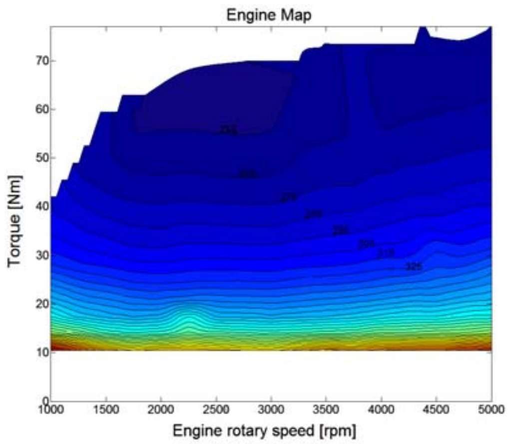

Fig. 4: Engine map

2.4 Electric motor model

The electric motor model is based on efficiency map of electric motor and inverter (Figure 5). Power efficiency is obtained by inputting the torque and motor rotary speed.

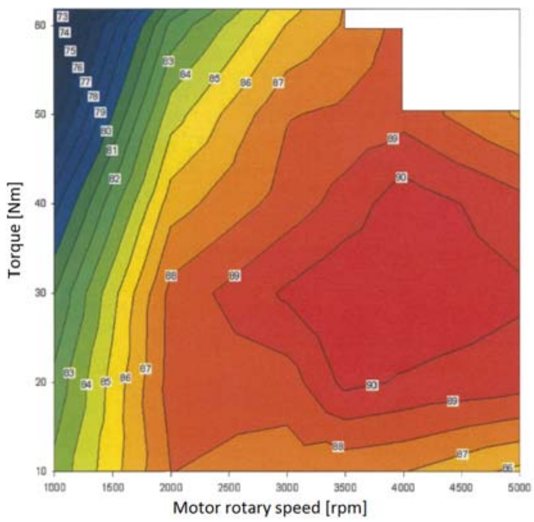

Fig. 5: Efficiency map of electric motor with inverter

2.5 Battery model

A nonlinear dynamic battery model is used in battery modeling [4]. In this method, the electromotive force *E* and internal resistance *r* are resolved in 6-order algebraic expression of battery SOC *k*.

$$E(k)=A_e k^6+B_e k^5+C_e k^4+D_e k^3+E_e k^2+F_e k+G_e \qquad (8)$$

$$R(k)=A_r k^6+B_r k^5+C_r k^4+D_r k^3+E_r k^2+F_r k+G_r \qquad (9)$$

Table 1 shows the factors in equation (8) and (9) for 30Ah/43V Li-ion module from SAFT company which is used in simulation. The approximated equation and factors are based on battery discharging characteristics obtained by experiments.

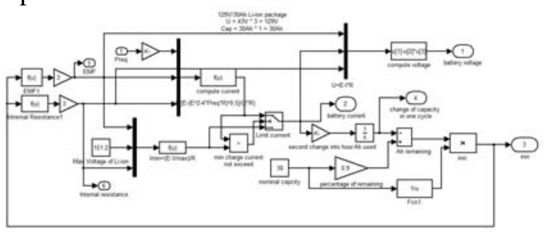

Fig. 6: The battery model in MATLAB SIMULINK

Table 1: Factors of equation (8) and (9) for 30Ah Li-ion battery module from SAFT:

Factors	Internal resistance during discharging R(k)	Electromotive force E(k)
A	0.71806	-28.091
B	-2.6569	157.05
C	3.7472	-296.92
D	-2.5575	265.34
E	0.8889	-119.29
F	-0.14693	30.476
G	0.023413	38.757

3 Simulation results

3.1 Simulation parameters

In order to analyze the influence of different control strategies and parameters, several comparison simulations were done under NEDC (New European Driving Cycle). An ultra-light basket-tube frame vehicle is considered as the vehicle model (Figure 7). The dimension of the car is 3m in length and 1.5m in width. Table 2 shows the parameters of planetary plug-in hybrid powertrain.

Fig. 7: The ultra-light basket-tube frame vehicle designed and prototyped by Prof. Szumanowski group

Table 2: Parameters of planetary plug-in hybrid powertrain and its 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
Basic ratio of planetary gear	1.99
Driving cycle	NEDC
Main reducer ratio	3.62
Reducer ratio between motor and planetary transmission	1.35
Battery	
Battery type	Li-ion
Battery pack number	3
Nominal voltage [V]	43*3
Nominal capacity [Ah]	30
PM motor	
Peak power [kW]	75
Continuous power [kW]	30
Maximal rotary speed [rpm]	5000
Nominal torque [Nm]	60
Maximal torque [Nm]	240
Thermal engine (Gasoline)	
Volume [cm^3]	1200
Maximal power [kW]	35
Maximal torque [Nm]	78
Rotary speed rang [rpm]	1000~5000

3.2 Basic control strategy

The control of whole powertrain is connected with clutch/brake operations. Table 3 shows the relation between control signal of clutch/brake system and operating modes of powertrain. In control strategy, vehicle speed, torque on transmission shaft and battery SOC are used as feedback signals for changing the operating mode of powertrain. The basic control method is listed as below.

- For starting, pure electric mode is enabled to reduce emission.
- For low speed and middle speed, control system determines the operation mode according to torque on transmission shaft and battery SOC. When torque is too low, pure electric mode is selected to avoid ICE working in a poor condition.
- For high speed mode, hybrid mode is selected when SOC is over threshold. If SOC is lower than threshold, pure engine mode is enabled to protect battery.

Table 3: Control signal of clutch/brake systems for different operating modes of plug-in hybrid powertrain

Operation mode of plug-in hybrid powertrain	**Control signal of clutch/brake systems**	
	Brake I*	***Clutch/Brake II*****
Pure electric drive and regenerative brake	off	off
Pure engine drive	on	on
Hybrid drive	off	on
Engine charge battery (when vehicle stop)	off	off

* 'on' indicates brake engaged; **'on' indicates clutch engaged and brake disengaged.

3.3 Comparison simulation for different control strategies

To investigate the influence of different control strategies, this paper sets up two control strategies for demonstration which are Strategy I and Strategy II. In Strategy I, it uses vehicle speed cooperated with torque on transmission shaft as feedback signal for changing operation mode. In Strategy II, it uses torque on transmission shaft cooperated with demand power as feedback signal for changing operation mode.

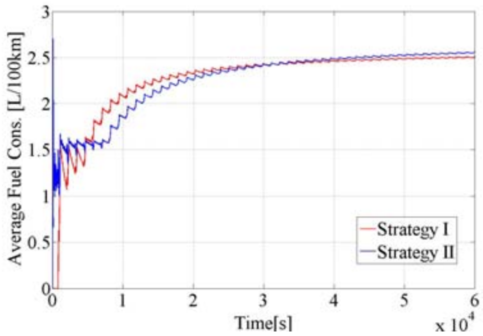

Fig. 8: Comparison of average fuel consumption in different control strategy

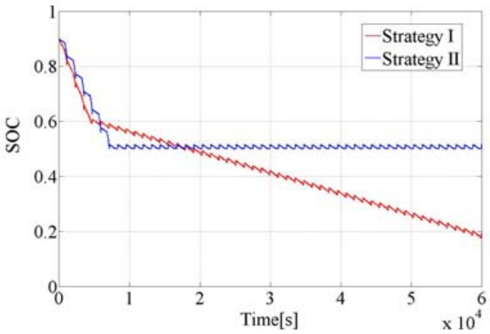

Fig. 9: Comparison of battery SOC in different control strategy

Figure 8 and 9 show the simulation results for Strategy I and Strategy II. For the same driving range (540km), fuel consumption of Strategy I is less than that of Strategy II by 2%. By the end of simulation, battery SOC is limited to the proper set value in Strategy II. While in Strategy I, battery SOC is out of control and decreases to 0.18. It means that the powertrain could work in hybrid mode for long distance driving to achieve better fuel economy without damaging the battery. Considering requirements of plug-in hybrid and similar fuel economy performance, Strategy II is better than Strategy I.

3.4 Simulation for pure electric drive

Battery capacity influences 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. According to simulation results, the hybrid powertrain could drive over 50km for pure electric drive with full charged battery.

3.5 Optimization of 2-step gearbox

The 2-step gearbox is an important element for the plug-in hybrid powertrain. With proper adjusted gear ratio and gear changing strategy, it could increase the energy efficiency for different driving conditions regarding to city traffic and suburban area.

Table 4 shows simulation results for different gear ratios. In these simulation experiments, driving range and battery conditions are the same. According to simulation results, smaller 2ed-gear ratio could achieve better fuel efficiency for high speed drive. However, by changing gear ratio, it also changes the operating points of ICE on engine map. With limitation of operating range, the adjustment of gear ratio should cooperate with observing the operating points to keep ICE working in efficient area.

Table 4: Comparison of simulation results for different gear ratios

1^{st}-gear	2ed-gear	Speed threshold for changing gear (km/h)	Average fuel consumption (L/100km)
1	1	80	1.796
1	0.95	80	1.784
1	0.9	80	1.735
1	0.85	80	1.684
1	0.8	80	1.636
1	0.75	80	1.575

The simulation results in Table 5 prove that the speed threshold for changing gear also has influence on fuel consumption.

Furthermore, the main reducer ratio and additional gear ratio between engine and planetary transmission are proper adjusted to cooperate with 2-step gearbox for minimizing fuel consumption.

Table 5: Comparison of simulation results for different speed threshold with the same gear ratio 1/0.8

Speed threshold for changing gear (km/h)	Average fuel consumption (L/100km)
50	1.696
60	1.676
70	1.653
80	1.636
90	1.619

4 Conclusions

This paper presents the method of designing plug-in hybrid powertrain with planetary transmission based on CHPTD. CHPTD is more compact and lower costs than other series-parallel hybrid drives equipped with planetary transmission and two motors. Dynamic model of the powertrain has been established in MATLAB SIMULINK environment. The simulation results show:

CHPTD is a suitable configuration for plug-in hybrid application. The advantage of planetary transmission is obtained by proper design and control of new electromagnetic clutch/brake device based on classic dual-diaphragm spring system.
Control strategy influences the performance of hybrid powertrain a lot. With proper designed 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 2-step gearbox increases the fuel efficiency in different driving conditions. According to comparison simulation results, the fuel consumption of hybrid powertrain with 2-step gearbox is decreased by 9% than that without 2-step gearbox.

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Authors

Prof. Antoni Szumanowski
Antoni Szumanowski is the professor of Warsaw University of Technology. He has been involved in hybrid electric vehicles research since 1976. He earned both Ph.D. and D.Sc. degrees from Warsaw University of Technology, where he is the leader of the Scientific Division which activity is supported by government and university grants. He is the member of AVERE.

Msc. Zhiyin Liu
Zhiyin Liu obtained Msc degree from the Automobiles and Construction Machinery Engineering Faculty of Warsaw University of Technology (WUT) in 2008. He has been the research assistant of Prof. A. Szumanowski since 2009 in the field of HEVs propulsion system simulation and components design.

Dr. Yuhua Chang
Yuhua Chang received the M.Sc. and Ph.D. degrees from Warsaw University of Technology (WUT), Warsaw, Poland, in 2005 and 2007, respectively. Since 2003, she has been a Research Assistant of Prof. A. Szumanowski in the field of battery modeling and management in HEVs and the configuration design of a propulsion system for HEVs by simulation.