Kinematic Study and Mode Analysis of a New 2-Mode Hybrid Transmission

Xuerui Ma, Yong Zhang and Chengliang Yin

Abstract A new 2-mode hybrid transmission for FWD mid-size passenger car integrated two electro-mechanical power-split operating modes. This new transmission includes two simple planetary sets with two transfer clutches and two braking clutches. With different activation of the four clutches, different modes can be obtained. In this chapter, firstly we analyze all modes and screen available ones respectively for pure electric propelling, engine-only propelling, hybrid propelling, engine-start, power generating, brake regenerating. The kinematic analysis based on the lever method researches both the speed and torque equation of available modes. Then we calculate and compare the max-torque capability of the propulsion modes to define the proper applications. Finally a numerical simulation of acceleration in the input-split mode runs in SimulationX.

Keywords Power-split · 2-Mode hybrid transmission · Kinematic analysis · Operating mode · Simulation

1 Introduction

Nowadays the power-split hybrid powertrain has become the main stream of hybrid electric vehicles. It absorbs both the advantages of the series and parallel hybrid architectures. And since the world most successful hybrid sedan Toyota

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X. Ma · Y. Zhang · C. Yin (✉)
National Engineering Laboratory for Automotive Electronic Control Technology, Shanghai Jiao Tong University, Shanghai, China
e-mail: mayipian@sina.com

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Prius hit the market, power-split architecture has drawn more and more attention and research interest.

The single mode power-split system consists of three different types, which are input-split, output-split and compound split according to the position where power-split happens. Summarized in [1] in general only the input split configuration is feasible as a full-range single mode hybrid system but requires high power, high output motor torque capability and high input motor speed capability. Output split systems are not feasible as single mode systems due to limits on achievable ratio coverage; however, they are useful as a sub-mode, especially at low gear ratio and engine start. The compound split mode is useful as a high range but not for launching due to poor efficiency and power circulating issues.

The combined of the input split and compound split is capable of providing full ratio coverage with moderate component speeds and torques and electrical path power less than 50 % of the engine peak. The compound split mode can work with low electrical losses during cruise conditions.

Among numerous power-split transmission designs two configuration, single-mode and 2-mode power-split transmissions, have big success in market. The most successful single-mode system is Toyota hybrid cars such as Prius and Lexus hybrid models.

GM has registered some 17 patents with different designs for 2-mode power-train, which contain a planetary architecture, two planetary gears and three planetary gears. The most popular configuration can be found in the 2008 GMC Yukon SUV and the 2008 Chevrolet Tahoe SUV. The configuration is a hybrid transmission with two EVT modes and four fixed gears [2].

There are also many designs from the researchers of some primary manufactories like Renault IVT and Timken [3].

In this chapter a new 2-mode hybrid transmission with 2 planetary gears and 4 clutches/brakes has been studied via kinematic analysis and its characteristics like operating modes, transmission efficiency and maximum output torque has been provided here. Then a simulation of acceleration in input-split mode is implemented in SimualtionX and has indicated the hybrid transmission architecture can provide enough acceleration in this mode for a mid-size sedan.

2 2-Mode Hybrid Transmission Characteristics

2.1 Operation Modes

A new 2-mode hybrid transmission which shown in Fig. 1 has two planetary gear sets, two clutches and two brakes denoted by PG1, PG2, C0, C1, B0 and B1.

Compared with the no clutch design like THS, the new hybrid transmission combines two kinds of Electric Variable Transmission (EVT) modes which are input-split and compound-split respectively through different clutches action. With

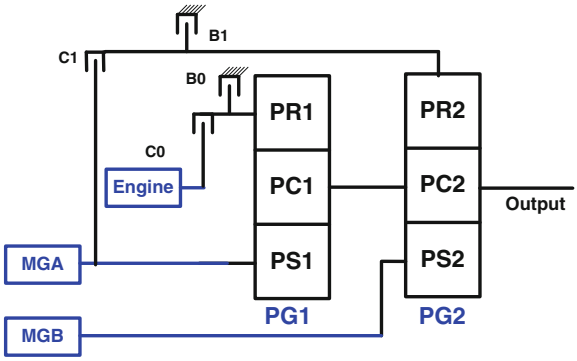


Fig. 1 Scheme of a new 2-mode hybrid transmission

the clutch C0 and brake B0 the engine can engage or disengage in the hybrid powertrain, which not only reduces the loss of engine spinning, but also add two Electric Vehicle (EV) modes.

This hybrid powertrain can realize all the functions of the HEV.

The full permutation of the four clutches and brakes applies 16 potential operation configurations. But considering the DOF (Degree of Freedom) of a planetary gear set, we eliminated the unreasonable configurations like lock up and spin of the planetary gear set. And the repeated operation configurations are also screened. Another influence factor in the selection of different operation modes is the control of motor/generator MGA/MGB and engine, e.g. in the same configuration with engaged C0 and C1, if the energy management has no power demand on MGB, only MGA and the engine cooperate as charging while engine driving; if the MGB works as a motor, the powertrain works as compound split driving.

Finally we have screened the feasible configurations which are described in Fig. 2.

15 operation modes can be obtained by engaging or disengaging the clutches and brakes. Especially there are multi electric vehicle modes, which provide the potential for Plug-in HEV. The hybrid system can select better operating range considering both the efficiency of the engine and the transmission. In contrary the mode selection and control will be more complicated.

2.2 Kinematics Analysis of the System

The lever diagram is an important tool that can directly indicate both the speed and torque relationship of the planetary gear system [4]. Hereinafter an example of compound split mode is analyzed in details and the following discussion is based on a quasi-static state neglecting the transient motions of the powertrain components.

The schematic and lever analogy of the compound split mode is shown in Fig. 3. This mode is the most representative because MGA is connected to the sun

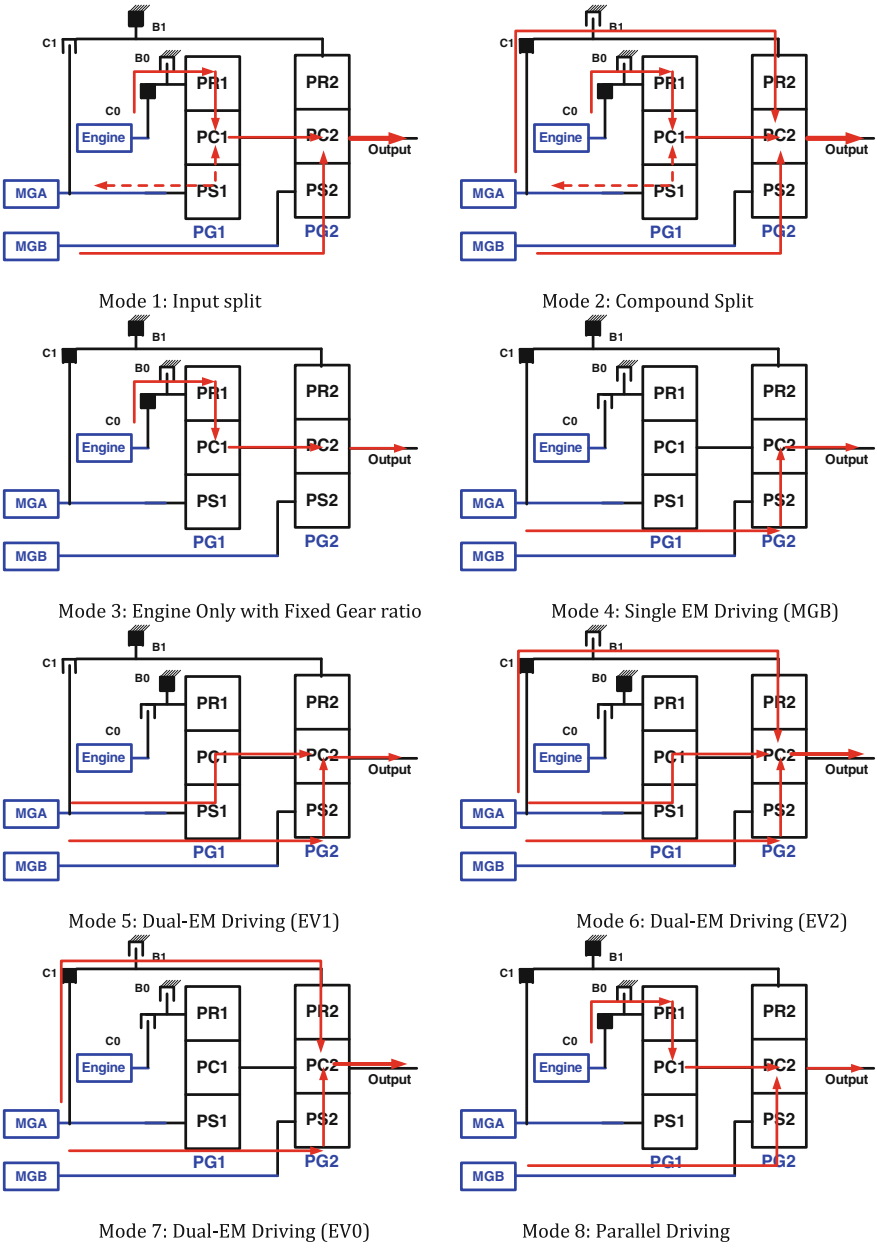
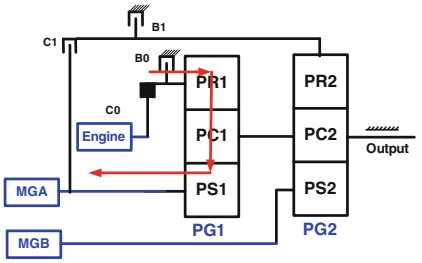
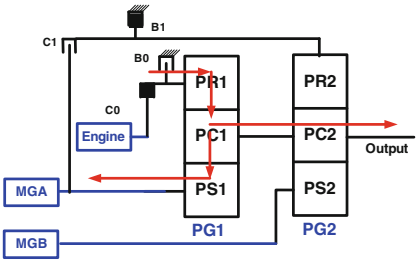


Fig. 2 Operation modes of the powertrain with this new 2-mode hybrid transmission.

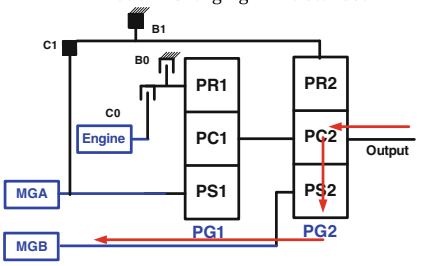
gear of the first planetary gear and the ring gear of the second planetary gear simultaneously. With two connected ports $PC1(PC2)$ and $PS1(PR2)$ between the two planetary gear sets a combined lever analogy can be simplified from the



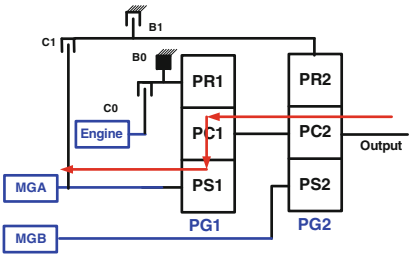
Mode 9: Charging while standstill



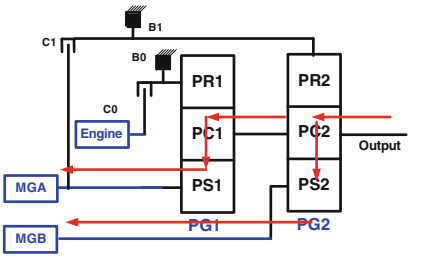
Mode 10: Charging while running



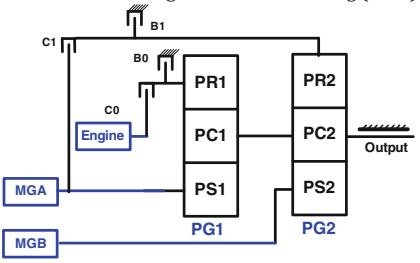
Mode 11: Single-Generator Braking (MGB)



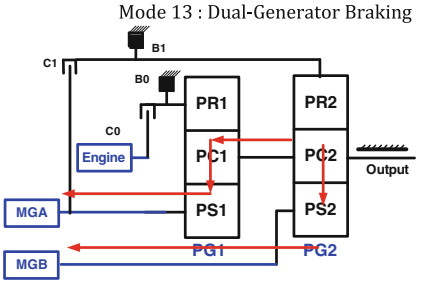
Mode 12: Single-Generator Braking (MGA)



Mode 13 : Dual-Generator Braking



Mode 14: Mechanical Braking



Mode 15: Compound Braking

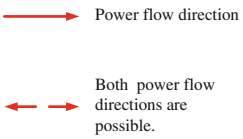


Fig. 2 continued

schematic as shown in Fig. 3c. The combined analogy is more forthright without interactional torque denoted as T_1 in Fig. 3b.

The rotational speed is denoted as ω_i and i represents the corresponding ports or components. The lever length ρ_1 and ρ_2 are equal to the teeth number ratio between the ring gear and sun gear of the two planetary gear sets respectively.

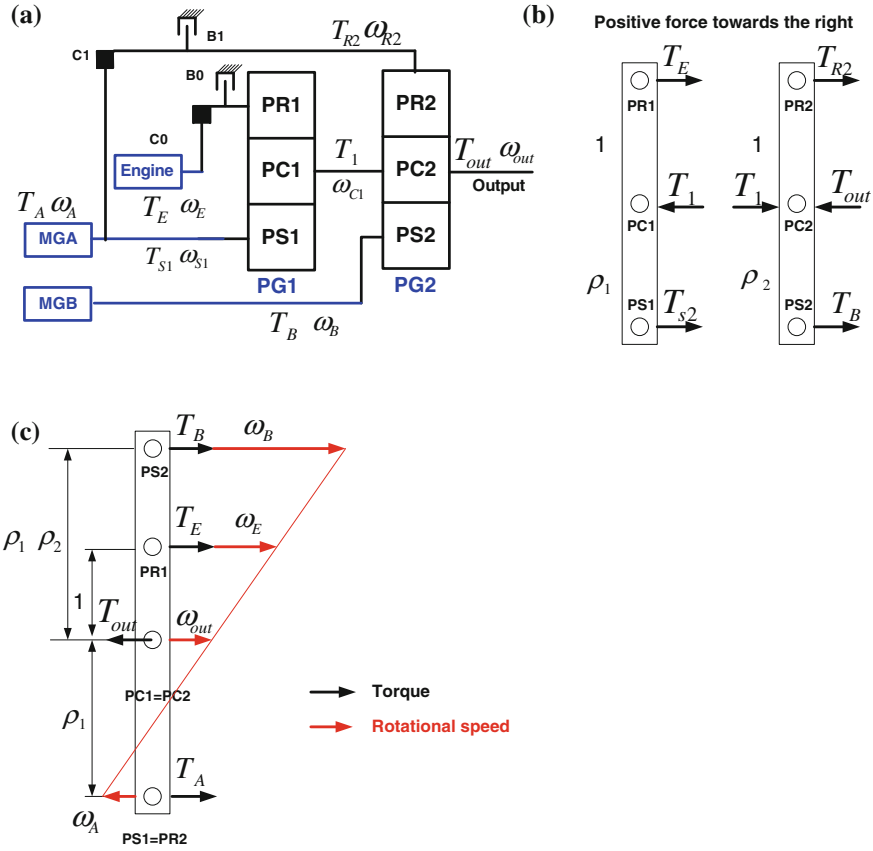


Fig. 3 Schematic and lever analogy of the compound split mode **a** Schematic of compound split mode, **b** Separate lever analogy, **c** Combined lever analogy

The equilibrium equations of static state can be presented as follows:

$$\omega_{out} = \frac{1}{1+\rho_1}\omega_A + \frac{\rho_1}{1+\rho_1}\omega_E \tag{1}$$

$$\omega_{out} = \frac{\rho_2}{1+\rho_2}\omega_A + \frac{1}{1+\rho_2}\omega_B \tag{2}$$

$$T_{out} = (1+\frac{1}{\rho_1})T_A + (1-\frac{1}{\rho_1\rho_2})T_E \tag{3}$$

$$T_{out} = (1+\frac{1}{\rho_1})T_E + (1+\rho_2)T_B \tag{4}$$

Table 1 Static equations of rotational speed and torque

Operation mode	Rotational speed equations	Torque equations
Input split	$\omega_{out} = \frac{1}{1+\rho_2}\omega_B$	$T_{out} = (1+\rho_2)T_B + (1+\frac{1}{\rho_1})T_E$
	$\omega_{out} = \frac{1}{1+\rho_1}\omega_A + \frac{\rho_1}{1+\rho_1}\omega_E$	$T_A = \frac{1}{\rho_1}T_E$
Engine only	$\omega_{out} = \frac{\rho_1}{1+\rho_1}\omega_E$	$T_{out} = \frac{1+\rho_1}{\rho_1}T_E$
EV 0	$\omega_{out} = \frac{1}{1+\rho_2}\omega_B + \frac{\rho_2}{1+\rho_2}\omega_A$	$T_{out} = (1+\rho_2)T_B = (1+\frac{1}{\rho_2})T_A$

When the road condition and driver demand are known as ω_{out} and T_{out}, the system has one rotational DOF and one torque DOF.

The EV 1 and EV 2 modes are the special cases of EVT modes when engine speed is zero. The equations of input split mode, engine only mode and EV 0 mode are shown in the Table 1.

3 Transmission Efficiency

Using the torque and speed relationships derived in previous kinematics analysis, the transmission efficiency and power characteristic for two EVT modes are then calculated [5]. In the efficiency analysis it is assumed that the efficiency of the mechanical path is 100 % and that of the motor/generator is 85 %. In order to calculate the transmission efficiency it is also assumed no power from battery was used which means the electric power between generator and motor is balanced and only engine power is delivered to the output shaft.

Table 2 shows the powertrain parameters that were used in transmission efficiency calculation and later maximum propelling torque calculation.

Speed ratio is defined as engine speed compared to output shaft speed. Power split ratio represents the electric power from the engine output [6]. The transmission efficiency and power split ratio versus speed ratio is shown in Fig. 4. The points of 100 % efficiency means there is no electric conversion loss and the engine output has been completely delivered to the output shaft. The points are known as mechanical points where the power split ratio is zero. The map of transmission efficiency can also be applied to define the operation range of the EVT mode as a limit.

For this 2-mode hybrid transmission the input split mode and compound split mode has a common point which is also the mechanical point. According to the kinematic analysis we know at this point the speed ratio is exactly equal to that of the engine only mode, which is also as a fixed gear. It is remarkable that this point is not only the transition between the two EVT modes but also a standalone mode when the engine can run under efficient area.

Table 2 Powertrain parameters

Parameters		
Planetary gear ratio ρ	PG1	PG2
	2.17	2.242
Final reduction gear ratio	2.87	
Tire radius	0.308 m	
Engine	57 kW, 115 Nm max. torque, 4,700 rpm max. speed	
MGA	15 kW, 55 Nm max. torque, 6,000 rpm max. speed	
MGB	30 kW, 305 Nm max. torque, 6,000 rpm max. speed	
Vehicle mass	1,413 kg	

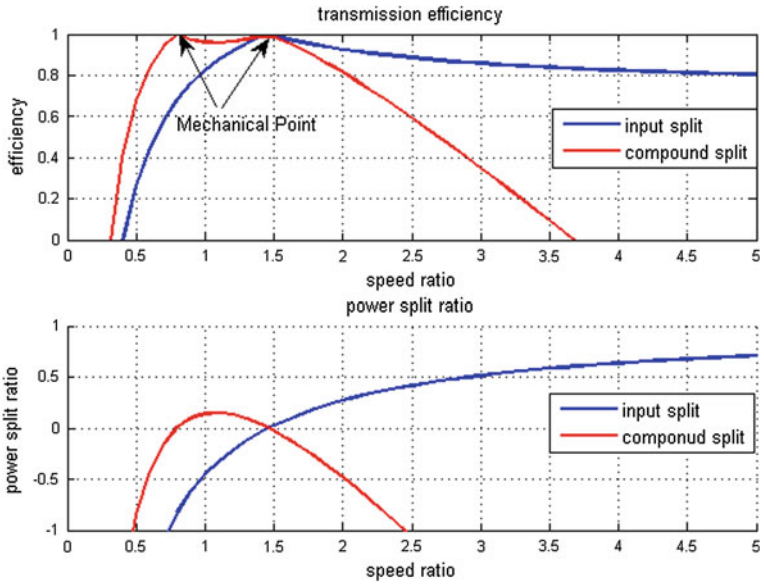


Fig. 4 Transmission efficiency and power split ratio

4 Maximum Propelling Torque Capability

Input-split, compound-split and engine only are the basic propelling modes. From the kinematic Eqs. (1)–(4) and Table 1, the maximum output torque can be calculated in iterative process [7]. The maximum output torque is shown in Fig. 5.

For the input split mode, it has a relatively higher torque capability for V = 0–74 km/h because the second planetary gear set with the ring gear locked acts as a reduction gear. But it is also limited when MGB reaches its maximum speed of 6,000 rpm from where the output torque is zero. The input split mode is quite suitable for low speed with high torque demand.

For the engine only mode, the maximum torque is lower because only the engine's torque used to propel the vehicle. And the engine works with a fixed gear

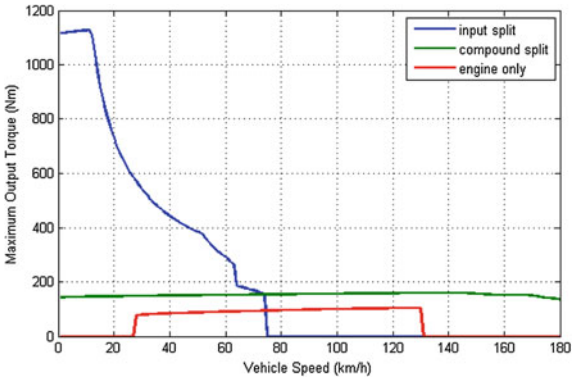


Fig. 5 Maximum output torque of three propelling modes

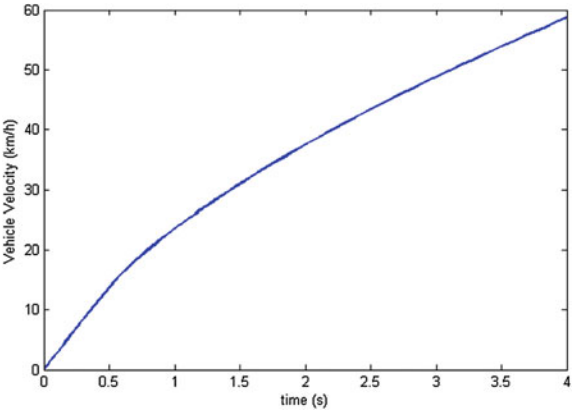


Fig. 6 Acceleration in the input split mode

ratio, so the effective velocity range is from 28 to 130 km/h limited by the engine idle speed and maximum speed. This mode is suitable for high speed cruise when engine works with high thermal efficiency. In addition with MGB is involved we can get the parallel mode.

For the compound-split mode, the maximum torque is steady for most of the velocity range. So this mode can supplement the output torque range besides the first two.

5 Simulation

The calculation in Part 3 gave out the maximum capability of the powertrain, but the actual performance is decided by the cooperation of all the power components. The input split mode has indicated high torque capability while low velocity. Therefore the simulation of the acceleration performance in such mode is implemented using SimulationX, which is a CAE software for physical system

simulation. Because of the input-split kinematic characteristic the engine can work decoupled from the wheel speed. During the acceleration the engine is working under a constant speed 2,000 rpm with high efficiency. The final velocity is then limited by MGB maximum speed. The acceleration curve is shown in Fig. 6. The acceleration time from 0 to 50 km/h is 3.14 s.

6 Conclusion

In this chapter, a systematic analysis of a new 2-mode hybrid transmission was implemented. The mode screening indicated that the transmission had various segmentations considering the driver demand. The efficiency analysis demonstrated the advantage of 2-mode hybrid which combined the input and compound split modes. And the engine only mode was the transition between input split and compound split modes, which had a fixed gear ratio that was equal to the mechanical point of input split mode. The maximum output torque calculation showed the capability of different propelling modes and provided the foundation for mode selection [7]. The simulation result showed the powertrain with this new 2-mode transmission had remarkable acceleration ability in the input-split mode which was adequate for mid-sized hybrid electric vehicles. Furthermore we will research on the transition between two EVT modes and the EV modes which are potential for Plug-in HEV.

References

1. Conlon B (2005) Comparative analysis of single and combined hybrid electrically variable transmission operating modes. SAE paper, no. 2005-01-1162
2. Grewe TM, Conlon BM, Holmes AG (2007) Defining the general motors 2-mode hybrid transmission. SAE Paper, 2007, no. 2007-01-0273
3. Miller JM (2006) Hybrid electric vehicle propulsion system architectures of the e-CVT Type. IEEE Trans Power Electron 21(3):759–767
4. Benford H, Leising M (1981) The lever analogy: a new tool in transmission analysis. SAE Paper, 1981, no. 810102
5. Jaeyoung K, Woulsun C, Sunghwa H, Jeongman P, Hyunsoo K (2011) Control strategy for dual-mode power split HEV considering transmission efficiency. IEEE Vehicle Power and Propulsion Conference (VPPC), 2011, Conference Publication, art. no. 6043008
6. Kukhyun A, Suk WC (2008) Developing mode shift strategies for a two-mode hybrid powertrain with fixed gears. SAE paper, 2008, no.2008-01-0307
7. Jeongmin K, Talchol K, Byungsoon M, Sungho H, Hyunsoo K (2011) Mode control strategy for two-mode hybrid electric vehicle using electrically-variable transmission (EVT) and fixed gear mode. IEEE Trans Veh Technol 60(3):793–803