Chapter 2
Configuration of Planetary Hybrid Power-Split System

In Chap. 1, the energy consumption characteristics of traditional vehicle have been analyzed by intuitive graphical method. Accordingly, the basic way of traditional vehicle energy saving is proposed. It’s a good choice to apply the hybrid technology to traditional vehicle in the short term. In recent years, the series-parallel hybrid vehicle has become the stream in the market. Most kinds of the series-parallel hybrid vehicles use planetary gears as the PSD. In this chapter, detailed introduction to the typical PSD configuration is given firstly, including THS of Toyota corporation and AHS of GM corporation. Then the working principle and analysis method for the two kinds of configurations are discussed in detail. Finally, a new kind of PSD configuration, DHS which is developed independently, is proposed and analyzed.

2.1 Typical Configuration of Planetary Hybrid System

2.1.1 Toyota Planetary Hybrid System

2.1.1.1 Toyota Single Planetary Configuration

Toyota corporation has granted a patent for invention in October 17th, 2000 [1], and the THS configuration was released which the first and second generation Prius adopted. The structure of THS is as shown in Fig. 2.1. Where 120 is the shell, 128 is sprocket wheel of ring output, 129 is the chain, 112 is a duplicate gear, 111 is the drive gear of final drive, 114 is differential, 139, 149 are torsional dampers, 150 is the engine, 156 is the power input shaft and MG1, MG2 are electric motors. The lever model of THS is shown in Fig. 2.2.
As can be seen from Fig. 2.1, in the THS configuration, the engine is connected to the planet carrier, and it transfers the power to the ring gear and the sun gear via planetary gears, the left end of the ring gear connects with the motor through the torsional damper, the right side of the ring gear connects with the drive shaft through the drive chain, the sun gear connects with the generator. According to the lever analysis method [2], the speed and torque relationships of the configuration can be got, which is shown as:

\[
\begin{align*}
    n_{out} &= \frac{1+k}{k}n_e - \frac{1}{k}n_{m1} \\
    T_{out} &= T_e \frac{k}{1+k} + T_{m2}
\end{align*}
\]

where \( T_{out} \) is the output torque of the system, \( n_{out} \) is the speed of output shaft; \( n_e \) and \( n_{m1} \) are engine speed and motor speed of MG1; \( T_e \) and \( T_{m2} \) are engine torque
and torque of motor MG2; \( k \) is the characteristic parameter of the planetary system, and it is equal to the ratio of the number of ring gear teeth and the number of sun gear teeth.

This system transmits most of the engine torque to the drive shaft directly through the ring gear, and few of the torque is transient to the generator by sun gear. Electric energy generated by the generator is used to charge the battery or drive the motor to enhance the driving force according to orders. This structure can decouple the speed and torque of the engine, and it can work as a continuously variable transmission by controlling the speed of engine and the torque of driving motor, by which it can allow the engine to operate continuously in the high-efficiency zone or low-emission zone. However, this configuration only has the input-split mode. Its specific operation modes are shown in Fig. 2.3.

This configuration is mainly used in the first and second generation of Prius vehicle. In December, 1997, Toyota corporation started to sale their first generation Prius, and released the second generation Prius in 2003 and the third in 2006. The main modification focused on the engine and electric drive system, and the power-split device was still the THS. In this system, Prius adopted the gear ratio 2.6 (gear ratio = number of ring gear teeth/number of sun gear teeth). The smart and precise planetary mechanism can redistribute the output power of the engine to achieve a reasonable balance of engine load.

Toyota raised another configuration in their patent in 1999 [3], and the configuration diagram is shown in Fig. 2.4. Where, 10 is the whole hybrid power system, 12 is the engine, 14 is the torsional damper, 16 is generator, 22 is driving motor, 22r is the rotor of electric motor, 18 is the power output component, 26 is the power output gear, 30 is the transmission gear, 28 is the gear shaft, 32 is transmission pinion, 34 is differential, 20 is planetary mechanism, 20r is the ring gear, 20 s is the sun gear, 24 is shaft of generator, 36 is generator controller, 38 is the drive motor controller, 40 is high voltage power supply.

This configuration is the third generation of Prius, the difference from the previous two generations is the connection way between the ring gear and drive axle. The first and second generations are four-axle structure, the engine, torsional damper, power coupling device, generator MG1 and motor MG2 are arranged in the
first axle, the transmission chain connects the first axle with the second one. Between the 2nd axle and 3rd axle is the intermediate gear, between the 2nd and 3rd shafts are the main drive gear. In contrast, the third generation Prius cancels the transmission chain and intermediate gear, which makes the weight lighter and the structure compact.

Toyota corporation got another patent license in 2000 [4], which introduced another single planetary power output device, and the configuration diagram is shown in Fig. 2.5. Where, 150 is engine, 130 and 140 are electric motors, 120 is the planetary gear, 121 is the sun gear, 124 is the planet gear, 122 is the ring gear, 123 is the planet carrier, 156 is the engine crank, 133 and 143 are stators of the two motors, 132 and 142 are rotors of the two motors, 160 is a clutch, 162 is a brake, 117,118 and 119 are rotational speed sensors, 165 is accelerator pedal position sensor, 166 is gear shift sensor, 114 is differential, 116 is the vehicle axle.

The main differences between this configuration and the third generation of THS are that it has a clutch (160) between planet gear (120) and electric motor (140) to realize the separation and connection of the two components, and that it sets a brake (162) to fix ring (122) while clutch (160) is separated in order to realize the series hybrid configuration, and come to a power-split hybrid configuration while clutch engaged. Changing modes according different running states of the vehicle can play the advantages of each mode, thereby improve the power and economy of vehicle. Detailed modes analysis are as follows:
Mode 1: clutch is separated and brake is engaged. The relationships of torque and speed are shown as Eqs. (2.3) and (2.4).

\[ T_{out} = T_{m2} \]  
\[ n_{out} = n_{m2} \]  

Mode 2: clutch is engaged and brake is separated. Under this mode, connecting style of the configuration is same to the first and second generation of Prius THS system. The relationships of torque and speed are shown as Eqs. (2.1) and (2.2).

From the above, it’s easy to see that the separation of clutch, in this configuration, can realize the separation between drive motor and engine inertial system. Through it, the driving ability of electric motor can be played out easily, at the same time pure electric driving ability will be promoted. The engine efficiency can be increased by series mode at low speed.

2.1.1.2 Toyota THS-C System

In 2001, Toyota launched their THS-C system [5]. It is a hybrid system consisting of THS and continuously variable transmission (CVT). Its configuration diagram is shown in Fig. 2.6.
It has some differences between the THS configuration shown below with THS. In this system the engine is connected with the sun gear and generator is connected with planet carrier. There is a brake B1 on the ring gear, the ring gear and the planet carrier are connected with CVT by clutch C1, C2 respectively, and CVT outputs the power to the drive axle. Furthermore, there are two rows of planets here, but they share the same planetary carrier. Its main view is shown in Fig. 2.7.

The speed equation is

\[
(k - 1)n_c = k \cdot n_r - n_s
\]

(2.5)

where \(n_c\), \(n_r\) and \(n_s\) are the speeds of the planet carrier, ring gear and sun gear, respectively.

THS-C is mainly used in Estima and Alphard. Estima has been launched in June, 2001. In the autumn of 2003, Toyota released Alphard based on Estima. These two types have the similar powertrain, the main improvement is about the control and security system. In Estima and Alphard, THS-C system is used in the front drive unit, the rear drive unit is powered by a separate rear motor, its configuration diagram is shown as Fig. 2.8.

Estima and Alphard are both MPVs (multi-purpose vehicle). Compared with sedans, MPV has a big and heavy body and consumes more fuel. Applying hybrid system in this kind of vehicle will be more effective in terms of CO\(_2\) emission reduction. The original THS system hugely dependent upon the drive motor, if the size of components of the THS system are enlarged and then applied the system on the MPV, the size of motor, inverter, power battery and so on also need to be enlarged, which will lead to a lot of problems in terms of cost, quality, loading and so on. So in Toyota corporation, the belt type CVT is used to supply the drive torque with a smaller motor. At the same time, the bulks of inverter and drive
Fig. 2.7 Main view of THS-C configuration

Fig. 2.8 Configuration diagram of THS-C dynamic system
battery are reduced. Besides, for a MPV which is four-wheel drive (4WD), the increased mass of drive shaft and other components will make it consume much more fuel compared with a 2WD vehicle, but in the electric 4WD, the designer could abolish some components like the drive shafts. And it is in 4WD mode only if necessary, and absorb braking energy through the front and rear motor to minimize the bad fuel consumption caused by 4WD. Furthermore, it changes the link relationship between the engine, generator and planetary, the engine is connected to the sun gear, generator is connected to the planetary, power is output through the ring gear. In this way, the torque of engine could be increased through the bigger ratio.

However, there are also many weaknesses in THS-C system. Most of the time, the system is a parallel configuration, for the reason that THS-C system in the front shaft and drive motor in rear shaft drive the vehicle at the same time, so it is difficult to ensure the balance of SOC, there is a risk that the battery cannot be used when the battery is insufficiently charged. Another problem is THS-C could realize both the function of THS system and CVT, and its mechanism is complex and costs more, which could be a key factor that limits its application. And the addition of CVT causes the system to require a motor to drive the hydraulic pump in it, which further exacerbates the complexity of the system structure. So the overall effect of THS-C is not so ideal. In January, 2006, the hybrid Estima was re-modified, not using the THS-C system any longer, but using the THS configuration directly. Because motor and generator are separated in THS II, the motor can be used to drive in any time during driving, and if the battery is undercharging, the generator can recharge it immediately, which improves the fuel economy. Experiments show that fuel consumption of Estima that adopt THS-II under 10–15 driving cycle is 5 L/100 km, while the fuel consumption of Estima that adopt THS-C is 5.5 L/100 km, that’s to say the new version has decreased 9% fuel consumption.

2.1.1.3 Toyota Dual-Planetary Configuration

Toyota corporation applied for an invention patent in 2005 [6]. this patent described a kind of hybrid vehicle power output device, which has a dual-planetary configuration and is shown as Fig. 2.9. Where, 20 is the whole hybrid system, 22 is the engine, 24 is the engine controller, 28 is the vibration damper, 26 is the crank, 30 is the planetary gear, 31 is the sun gear, 32 is the ring gear, 33 is the planet, 34 is the planet carrier, 32a is the ring gear shaft, 35 is the reduction gear, 60 is gear mechanism, 62 is the differential, 63a, 63b are drive wheels, 41, 42 are inventers, 50 is the battery, 54 is the power line, 40 is the motor controller, 43, 44 are rotor position sensors, 46 is the motor speed sensor, 47 is the current sensor, 70 is the vehicle control unit, 52 is the battery controller, 51 is the temperature sensor, 80 is the ignite signal, 81 is the transmission control lever, 82 is the position sensor of transmission control lever, 83 is the acceleration pedal, 84 is the position sensor of acceleration pedal, 85 is the brake pedal, 86 is the position sensor of brake pedal, 88 is vehicle speed sensor.
As can be seen from the above figure, engine connects with the front planetary carrier through the torsional damper, the front sun gear connects with motor MG2, the rear planetary carrier is fixed, so the motor MG2 can transfer power to the rear ring gear in fixed ratio. At the same time, the front ring gear connects with the rear ring gear, power is coupled here and then be transferred to the drive axle (Fig. 2.10).

Fig. 2.9 Dual-row planetary configuration diagram of THS

Fig. 2.10 Dual-row planetary lever model of THS
From the configuration diagram, the relationships of torque and speed are shown as below:

\[ T_{out} = T_e \frac{k_1}{1 + k_1} + T_{m2} \cdot k_2 \quad (2.6) \]

\[ n_{out} = \frac{1 + k_1}{k_1} n_e - \frac{1}{k_1} n_{m1} \quad (2.7) \]

Hermance and Abe have also made some research on this configuration [7]. This configuration adds a planetary gear, and becomes triple-axle from the original four-axle, which causes the configuration more compact. And it realizes the torque increase and speed reduction of the motor through fixing the rear planetary carrier, which improves the torque output capacity of the drive motor. But it has only one operating mode due to the rear planetary is a simple gear mechanism [8].

The configuration described in this patent is applied in three types of HEV of Toyota corporation, Lexus RX400h, Camry and Lexus Highlander [9]. After comparing Eqs. (2.2) and (2.6), several conclusions can be drew: this configuration is modified on the basis of the Prius configuration so that the drive motor is not directly connected to the front planetary ring gear but is connected to the front ring gear by the rear transmission. For the rear planetary, \( k_2 = 2.478 \). As a result, the system can output more torque, so Lexus RX400h, Camry and Lexus Highlander can achieve better power and off-road than the Prius without increasing the size of the drive motor.

### 2.1.1.4 Ravigneaux Configuration of Toyota Corporation

Toyota corporation launched Lexus GS450h vehicle in 2007, which adopts a special dual-planetary configuration. This configuration belongs to the second generation hybrid system of Toyota—THS-II, which is also called input-split Multiplication, and the configuration diagram is shown in Fig. 2.11 [10].

As can be seen from the above figure, the front planetary is just a normal one, but the rear is a Ravigneaux planetary mechanism, which is also called a compound planetary gear. It combines two common planetary gears into a power coupling device, includes two sun gears, the front sun gear 2 and the rear sun gear 3. And it also contains a compound planetary carrier, which is a combination of two planetary carriers with different radius, the small planet carrier mesh with the front sun gear and the inside of the larger one mesh with the rear sun gear, its outside gears engage with the ring gear. It is obviously that this kind of compound planetary configuration could be seen as dual-planetary which sharing the same planet carrier and ring gear.

In 22nd, March, 2005, Toyota launched the other two high power full hybrid SUVs (sport utility vehicle), Harrier and Kluger, which both adopt the THS-II configuration shown above. Harrier and Kluger hybrid SUV have good fuel economy. America Environmental Protection Agency (EPA) published that fuel
economy of Harrier reached 7.8 L/100 km, 30% lower than conventional vehicles. Later, this kind of configuration became the main configuration of Toyota corporation. In 2007, it was applied to the Lexus LS600hL.

This configuration includes an engine, a dual-planetary gear, a generator, a drive motor and two brakes. The rear planetary mechanism can provide two ratios for 1.9 and 3.9 by different states of the brakes. So that it can achieve two different operation modes to fulfil the high speed cycles and the low speed cycles. The curves of mode switch are shown in Fig. 2.12.

(1) Low speed mode (high load)

In low speed mode, the rear ring gear R2 of Lexus GS450h is braked, the rear small sun gear is in idle state, the configuration diagram and lever model are shown as Figs. 2.13 and 2.14.

The torque relationship can be derived from the above configuration diagram:

\[ T_{out} = T_e \frac{k_1}{1+k_1} + T_m(1+k_2) \] (2.8)

Fig. 2.11  Simplified configuration diagram of Lexus GS450h

Fig. 2.12  Mode switch curves of Lexus GS450h
(2) High speed mode (low load)

In high speed mode, the rear smaller sun gear is braked, the rear ring gear is in idle state. Configuration diagram and lever model are shown in Figs. 2.15 and 2.16.

The relationships of torque and speed are shown as below:

\[
T_{out} = T_e \frac{k_1}{1 + k_1} + T_{m2} \frac{k_2 + k_3}{k_3} \tag{2.9}
\]

\[
n_{out} = n_e \frac{1 + k_1}{k_1} - \frac{1}{k_1} n_g \tag{2.10}
\]

where \(k_1 = 2.6\), \(k_2 = 2.9\), \(k_3 = 3.2\).
After putting the specific values into the formula, it can be calculated out that: Lexus GS450h can output a larger torque in the low-speed mode, and can also get better power performance in high-speed mode. So at high speed, it can achieve better acceleration performance than the average hybrid constructions.

2.1.1.5 Summary of EVT Configurations of Toyota Corporation

Looking at the development route and technical achievements of the Toyota corporation in the EVT hybrid coupling system, the technical route of the dynamic coupling configuration can be concluded as shown in Table 2.1 and Fig. 2.17. From single-row to the dual-row, from Prius to Lexus GS450h, the development of EVT configurations of Toyota corporation is extremely clear: always with the initial THS configuration as the core, and on this basis for the development, diversification, complexity, and thus produce a variety of other superior performance configurations.
### Table 2.1 EVT configurations of Toyota

<table>
<thead>
<tr>
<th>Single-row</th>
<th>Invention time</th>
<th>Source of literature</th>
<th>Vehicle</th>
<th>Configuration</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>US 6131680</td>
<td>The first/second Prius</td>
<td>THS</td>
<td>Former Prius — EVT classic structure, realize power-split</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>US 5934395</td>
<td>The third Prius</td>
<td>THS</td>
<td>Change the chain link of the original Prius to the gear transmission</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>SAE2002-01-0931 paper</td>
<td>Estima Alphard</td>
<td>THS—C System</td>
<td>The characteristics of planetary and the CVT are integrated, which is suitable for MPV</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>CN1336879A</td>
<td></td>
<td>THS + Clutch</td>
<td>For the improvement of the original Prius, more than one clutch and a model</td>
<td></td>
</tr>
<tr>
<td>Dual-row</td>
<td>2005 CN1819934A</td>
<td>Lexus RX400h Camry Lexus highlander</td>
<td>Single + single</td>
<td>Prius increase a deceleration of the speed ratio</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>SAE2007-01-0296</td>
<td>Lexus GS450h Harrier Kluger Lexus LS600hL</td>
<td>Single + Ravigneaux</td>
<td>Prius increase two deceleration of the speed ratio</td>
<td></td>
</tr>
</tbody>
</table>

### 2.1.2 GM Planetary Hybrid System

#### 2.1.2.1 Dual-Planetary Configuration [11]

American GM corporation has published their patent early in 1996 [12], describing an input-split hybrid dual-planetary gear mechanism. It is an early planetary configuration, the engine and electric motor are not connected with the planetary gear.
directly. Therefore, its structure is complex and has not been used for a long time. The configuration diagram is shown in Fig. 2.18. Where, 110 stands for the whole hybrid system, 124 is engine, 112 is engine crank, 120 is generator, 122 is electric motor, 168, 142 and 154 are clutches, 114 is planetary gear, 132 is ring gear, 136 is planetary gear, 134 is sun gear, 138 is planetary carrier, 139 is output shaft of ring gear, 140 is output shaft of sun gear, 166 and 163 are transmission gears, 160A is output gear, 118 is power output shaft, 174 is differential, 170 and 172 are half axles, 176 is driving wheel, 126 is battery, 128 is electric control unit, 130A, 130B, 130C, 130D, 130E and 130F are power lines.

In 2002, GM corporation published a patent which introduces a new dual-planetary hybrid power-split device [13], called the Timken system, its diagram is shown in Fig. 2.19.

There are one engine, two motors, two clutches and two brakes in this configuration. The engine connects to the front ring gear, the front planetary carrier is connected to the rear planetary carrier, the front sun gear connects to the generator and also connects with the rear ring gear through the clutch, the rear sun gear is connected to the drive motor, the rear ring gear is connected to the brake, both the front and rear carriers connect to the output shaft. By controlling the clutches and brakes, it can realize different operating modes. Analysis about this is shown as below:
Fig. 2.18  Triple-row configuration diagram of GM in early time

Fig. 2.19  Timken system configuration diagram
(1) Low speed mode (high load)

C1 is engaged, C2 is separated, B2 is engaged, B1 is separated. The lever model is shown in Fig. 2.20.

The relationships between torque and speed are as follows:

\[
T_{out} = T_e \frac{k_1 + 1}{k_1} + T_m (k_2 + 1)
\]

\[
n_{out} = \frac{1}{1 + k_2} n_m
\] (2.11) (2.12)

(2) High speed mode (low load)

C1 and C2 are engaged, B1 and B2 are separated. The lever model is shown in Fig. 2.21.

The relationship between these speeds is:

\[
n_{out} = \frac{k_2}{1 + k_2} n_m + \frac{1}{1 + k_2} n_m
\]

In 2005, Xiaolan Ai from the Timken corporation and Scott Anderson [14] from Ricardo Inc. simulated and analyzed this configuration, its torque curves are shown in Fig. 2.22 and its mode classifications are shown in Table 2.2.

The results show that this configuration improves the acceleration performance and reduces fuel emissions compared to conventional 4WD vehicles. When calculated in unit of MPG, the fuel economy increased by 158% under FTP driving cycle, and increased by 92% under HWFET driving cycle. This configuration demands a less motor capability than the Prius does: the maximum motor torque request is only one third of the Prius, and maximum power is two thirds. Through comparing this configuration with Prius in economy efficiency and dynamic, the
conclusion is that this configuration is better, some of the contrast curves are shown as Figs. 2.23, 2.24, 2.25 and 2.26:

In 2003, GM corporation issued another patent [15], which developed a dual-row dual-mode planetary power-split device, referred to as AHS (2PG), and its configuration diagram is shown in Fig. 2.27.

It can be seen from the configuration diagram: engine 12 connects with front planetary carrier 26 by clutch 16, the front sun gear 24 is connected to the generator 56 and is connected to the rear ring gear 32 by a clutch 64. The rear ring gear connects to the vehicle frame 54 by clutch 62, the front ring gear 22 connects to rear sun gear 36 and the drive motor 68. This configuration can realize two modes which are suitable for the high speed low load condition and the low speed high load condition respectively by controlling the connection and separation condition of clutch 64 and 62, in order to optimize the engine operation points and improve the
fuel economy. This configuration is mainly used in Yukon and Tahoe of GM corporation, and is suitable for the SUV with high power requirement.

(1) Low speed mode (high load)

Clutch 64 of the AHS (2PG) is separated, clutch 62 is engaged, which means the rear ring gear be locked. The diagram for the configuration in low speed mode and its lever model are shown in Figs. 2.28 and 2.29 respectively.
The torque relationship between the components is as:

\[ T_{out} = (1 + k_2) \left( T_e \frac{k_1}{1 + k_1} + T_{m2} \right) \]  

(2.14)
High speed mode (low load)

Clutch 62 of the AHS (2PG) is separated and clutch 64 is engaged. The diagram in high speed mode and its lever model are shown in Figs. 2.30 and 2.31 respectively. The torque and speed relationships between the components are as follows:

\[
T_{\text{out}} = (1 + k_2) \left( T_e \frac{k_1}{1 + k_1} + T_m^2 \right) \tag{2.15}
\]

\[
n_{\text{out}} = \left( \frac{1 + k_1}{k_1} \right) \left( \frac{1}{1 + k_2} \right) n_e - \frac{1 - k_1 k_2}{k_1 (1 + k_2)} n_{m1} \tag{2.16}
\]
Fig. 2.27  AHS (2PG) configuration diagram

Fig. 2.28  Low speed mode configuration diagram of Yukon
The following conclusions can be drawn by taking the specific value into the formula: In high speed mode, the effect of acceleration for Yukon is less obvious, furthermore it needs MG2 operating at high speed. In the low speed mode, Yukon has an output torque larger than the usual hybrid vehicles and thus has more powerful actuation, so Yukon is a large-scale SUV.

Fig. 2.29 Low speed lever model of Yukon

Fig. 2.30 Diagram in high speed mode of Yukon
2.1.2.2 Triple-Planetary Gear Configuration [16]

1. AHS (3PG) configuration

In 1999, Schmidt published a patent [17], which introduced a kind of triple-planetary gear power-split configuration, referred to as AHS (3PG). Its configuration diagram and lever model are shown in Figs. 2.32 and 2.33 respectively.

Fig. 2.31 Lever model in high speed mode of Yukon

Fig. 2.32 Diagram of AHS (3PG)
The engine 14 connects to the ring gear of the first planetary, generator 56 connects to sun gear 32 of the first planetary and the ring gear of the second planetary, the planetary carrier 36 of the first planetary connects to the planetary carrier 44 of the second planetary and it also connects to planetary carrier 52 of the third planetary by clutch 62, the planetary carrier of the third planetary connects to output shaft 64, the sun gear 40 of the second planetary connects to the sun gear 48 of the third planetary and drive motor 72, the ring gear 46 of the third planetary connects to frame 68 by clutch 70. This system realizes two modes of high speed and low speed by controlling the separation and connection of the clutches.

2. Configuration of AHS (3PG) with 4FG ratio

In 2007, Tim M. Grewe, Brendan M. Conlon and Alan G. Holmes from GM introduced a new triple-row planetary gear configuration, which was produced on the basis of AHS by adding two clutches C3 and C4. Its configuration diagram and lever model are shown in Figs. 2.34 and 2.35 respectively.
After increasing the two clutches C3 and C4, four operating modes are also added: the dual-mode (high speed and low speed) and the four fixed speed ratio (FG) modes. This configuration is applied to the new version Yukon and Tahoe vehicles. Kaehler from GM also analyzes the new configuration [18], results show that this configuration is suitable to the heavy vehicle and SUV with large power, for it optimizes the fuel economy and meets the off-road performance of SUV. Its various models are analyzed as follows

(1) EVT1 mode (for low speed)

The EVT1 mode is amount to an input-split configuration, in this mode, only clutch C1 is engaged and all the other clutches are separated. The simplified model is shown as Fig. 2.36.

The torque and speed relationships between the components are as follows:

\[
T_{\text{out}} = \left( T_e \frac{k_1 + \frac{1}{k_1}}{k_2 + 1} + T_{\text{MB}} \right)(k_3 + 1) \tag{2.17}
\]

\[
(1 + k_3)n_{\text{out}} = \frac{1 - k_1 k_2}{1 + k_1} n_{\text{MA}} + \frac{k_1 + k_1 k_2}{1 + k_1} n_e \tag{2.18}
\]
From the equations above, EVT1 has the function of continuous variable transmission, which could adjust ratios by controlling the speed of the electric motor.

(2) EVT2 mode (for high speed)

EVT2 mode is amount to a compound power-split configuration, only the clutch C2 is engaged, and the other clutches are separated, the simplified model is shown in Fig. 2.37.

The torque and speed relationships between the components are as follows:

\[ T_{out} = T_e \frac{k_1 + 1}{k_1} + T_{mb}(k_2 + 1) \]  
\[ (1 + k_1)n_{out} = n_{mA} + k_1 n_e \]

Similar to the EVT1, EVT2 also has the function of continuous variable transmission, which could adjust ratios by controlling the speed of the electric motor.

(3) FG1: clutch C1 and C4 are engaged (Fig. 2.38)

The torque and speed relationships between the components are as follows:

\[ n_{out} = \frac{1}{k_3 + 1} n_e \]  
\[ T_{out} = (T_e + T_{mb})(k_3 + 1) \]

Both ratios of the two planetary are 1 at this time, and the PG1, PG2 are self-locking.

(4) FG2: clutch C1, C2 are engaged (Fig. 2.39)

The torque and speed relationships between the components are as follows:

\[ n_{out} = \frac{k_1 k_2}{k_1 k_2 + k_3} n_e \]
The torque and speed relationships between the components are as follows:

\[ T_{out} = T_e \left( \frac{k_3}{k_1 k_2} + 1 \right) T_m B (k_3 + 1) \]  

(2.24)

(5) FG3: clutch C2, C4 are engaged (Fig. 2.40)

The torque and speed relationships between the components are as follows:

\[ n_{out} = n_e \]  

(2.25)
\[ T_{out} = T_e + T_{mb} \]  

(2.26)

At this time, PG1, PG2, PG3 are all self-locking, and the gear ratio is 1.

(6) FG4: clutch C2, C4 are engaged (Fig. 2.41)

The torque and speed relationships between the components are as follows:

\[ n_{out} = \frac{k_1 k_2}{k_1 k_2 - 1} n_e \]  

(2.27)

\[ T_{out} = T_e \left( 1 - \frac{1}{k_1 k_2} \right) \]  

(2.28)

The comparisons of EVT1 mode and EVT2 mode are shown as below:

Comparison of torque: make subtraction of the torque equation in EVT1 and EVT2, the difference is:

\[ \Delta T_{out} = T_e \left[ \frac{k_1 + 1}{k_1 (k_2 + 1)} + T_{mb} \right] (k_3 - k_2) \]  

(2.29)

Generally, \( k_3 > k_2 \), so \( \Delta T_{out} > 0 \), which means EVT1 has a larger torque thus suitable for the low speed and starting mode. Substituting parameters of Lexus GS450h, \( k_1 = 2.6, k_2 = 2.9, k_3 = 3.2 \), into the equation above, the following result can be drawn:

\[ \Delta T_{out} = 0.11T_e + 0.3T_{mb} \]  

(2.30)

It is obvious that EVT1 has a larger torque output than EVT2, and is more suitable for the low speed mode.

Comparison of rotary speed: substituting parameters into the equation, the following relationships can be drawn:

Fig. 2.41 Diagram of FG4 mode
EVT1: \[ n_{out} = -0.43n_{mA} + 0.67n_e \]
EVT2: \[ n_{out} = 0.28n_{mA} + 0.72n_e \]

Above all, EVT1 is more suitable for low speed mode and EVT2 for high, the tipping point for switching EVT1 and EVT2 is FG2. The operating areas in various modes are shown in Figs. 2.42, 2.43 and 2.44, where the 4 black points stand for the 4 fixed gear ratio, and ‘inverse transmission ratio’ is the ratio of the output speed to the input speed.

3. 2MT with 4FG configuration

In 2009, Hendrickson et al. [19] and Meisel [20] introduced a new 2MT + 4FG configuration. The configuration is used in front drive vehicle and is also the first type of 2MT + 4FG for the front drive. It is used in the Saturn Vue Green Line vehicle of GM corporation and is named 2MT70. It is a configuration with tree planetary gears, but is usually considered as a dual-planetary configuration when analyzing its characteristics, Fig. 2.45 shows its configuration diagram.

Mode classification of the 2MT70 is shown in Table 2.3.

Each of the 4 fixed ratios has their own characteristics and actions:

(1) FG1 is equivalent to locking the PG1 and does not change the speed. So, it could provide the largest traction force in these 4 ratios. As a parallel mode, both the motor A and motor B can provide extra torque;

(2) FG2 is equivalent to locking motor A to make its rotary speed to be 0, it is the first mechanical point (that means all of the engine power is transferred through

![Fig. 2.42 Operating areas of AHS (3PG) with constant ratio](image)
mechanical path). It can realize the switches between two EVT modes. As a parallel mode, motor B can provide the extra torque;

(3) FG3 is equivalent to locking PG1 and PG2, so that the overall ratio of the system is 1, it could provide an ideal grade ability and traction ability. As a parallel mode, both the motor A and motor B can provide extra torque;

(4) FG4 is equivalent to locking motor B to make its rotary speed to be 0, it is the second mechanical point. It is the fixed ratio which suits cruise at high speed. As a parallel mode, motor A could provide extra torque.

2MT70 configuration has many advantages: (1) the full-featured dual-mode hybrid drive unit successfully applied in the general front drive structure; (2) maximize the fuel economy on the premise that doesn’t sacrifice much of the
power performance; (3) adding an innovative vibration damper bypass system, so that the engine starts and stops technology becomes the industry leader.

The performance improvements of 2MT70 are shown as Table 2.4. The fuel economy improvements of 2MT70 are shown as Fig. 2.46.

Besides, GM corporation published a patent in 1999 [21], which introduced a triple-planetary power-split configuration. This configuration is similar to the configurations presented above and researchers have little research on it, so the utilization rate is not high. The engineer of GM published patents in 2007 [22], which introduced diagrams of 15 kinds of triple-planetary configurations, almost all the

---

### Table 2.3 Mode classification of 2MT70

<table>
<thead>
<tr>
<th>Clutch work mode</th>
<th>CB12R</th>
<th>C234</th>
<th>C13</th>
<th>CB4</th>
<th>DBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV drive</td>
<td>EV</td>
<td>Engage</td>
<td>\</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Engine on/off</td>
<td>ESS</td>
<td>Engage</td>
<td>\</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Lows speed EVT</td>
<td>EVT1</td>
<td>Engage</td>
<td>\</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Fixed ratio 1</td>
<td>FG1</td>
<td>Engage</td>
<td>\</td>
<td>Engage</td>
<td>\</td>
</tr>
<tr>
<td>Fixed ratio 2</td>
<td>FG2</td>
<td>Engage</td>
<td>Engage</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>High speed EVT</td>
<td>EVT2</td>
<td>\</td>
<td>Engage</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Fixed ratio 3</td>
<td>FG3</td>
<td>\</td>
<td>Engage</td>
<td>Engage</td>
<td>\</td>
</tr>
<tr>
<td>Fixed ratio 4</td>
<td>FG4</td>
<td>\</td>
<td>Engage</td>
<td>\</td>
<td>Engage</td>
</tr>
</tbody>
</table>
configurations. And samples for ratio designing were given, while the detail analysis was not conducted. One of the configurations in this patent is shown as Fig. 2.47.

2.1.2.3 Summary of EVT Configurations of GM Corporation

Looking at the development route and technical achievements of the GM EVT configurations, the summary of its scientific research achievements route is shown as Fig. 2.48. Configurations of GM corporation are more complex, mainly focus on the dual- and triple-planetary configurations, especially published some patents in the triple-planetary configurations respect, as shown in Table 2.5.

2.1.3 Summary

Through the comparison of the EVT configurations of Toyota and GM, it can be found that AHS system of GM is nimbler to control for the many power-split modes
Fig. 2.47  Diagram of GM’s early triple-planetary configuration

Fig. 2.48  Configurations evolution roadmap of GM corporation
it could work in. So it is better than the Toyota THS system in both overall efficiency and power performance. But the AHS system always includes two or three planetary gears and several clutches and brakes, this makes it more complex, more difficult to manufacture, and its control strategy quite complicated.

### 2.2 Operating Principle of Planetary Hybrid System

Based on the typical EVT configurations, the general analysis model for the power-split device is built in this section, which is the core component of EVT system. Through the discussion of its speed and torque relations, the basic working principle of EVT system is obtained. Furthermore, the EVT system configuration is classified according to the characteristics of the planetary coupling device to explain the different types of features.
2.2.1 Basic Principles of Planetary Power-Split Device

Based on the lever mode for EVT parallel-series hybrid system, a static analysis mode is build, which is shown in Fig. 2.49.

where $\omega_A$ and $T_A$ are the rotary speed and torque of MG1 respectively, $\omega_B$, $T_B$ stand for the rotary speed and torque of MG2, $\omega_i$ and $T_i$ are rotary speed and torque of engine respectively, $\omega_o$, $T_o$ are the gear speed and torque of the planetary which connects to the drive axle.

According to the force balance of the system, the following conclusion can be drawn:

$$T_A + T_B + T_i = T_o \quad (2.31)$$

Seeking torque according to the point O, the following equation can be obtained:

$$T_i + \alpha T_A + \beta T_B = 0 \quad (2.32)$$

The relations of speed:

$$\frac{\omega_i - \omega_o}{1} = \frac{\omega_A - \omega_o}{\alpha} = \frac{\omega_B - \omega_o}{\beta} \quad (2.33)$$

Based on the Eqs. (2.31), (2.32), and (2.33), the following equation can be obtained:

$$\begin{align*}
\omega_A &= \alpha \omega_i + (1 - \alpha) \omega_0 \\
\omega_B &= \beta \omega_i + (1 - \beta) \omega_0 \\
T_i &= -\alpha T_A - \beta T_B \\
T_o &= (1 - \alpha) T_A + (1 - \beta) T_B
\end{align*} \quad (2.34)$$

Fig. 2.49 Static characteristics analysis model of EVT hybrid system
For this type of EVT series-parallel hybrid system, the power of engine is transferred to the wheels in two paths to drive the vehicle. One is mechanical path in which the engine power is transferred to the wheels through the gear mechanism directly; the other is electric path (engine → motor MG1 → motor MG2), in this path, electric motor MG1 absorbs part of the engine power and translates them into electric power then drives motor MG2 to move the vehicle or charge the battery (SOC of the battery lower than the up limit). Obviously, the mechanical path has a higher efficiency than the second electric path for it has no second pass of energy. So, when the input/output speed ratio reach the mechanical point (that’s to say one of the motors speed is 0), the efficiency of driveline is the largest.

For a input-split hybrid vehicle, Eq. (2.34) indicates that there is only one mechanical point, when \( \omega_A = 0 \), it can be expressed as Eq. (2.35):

\[
\frac{\omega_i}{\omega_o} = \frac{\alpha - 1}{\alpha}
\]

(2.35)

For compound-split hybrid vehicle, Eq. (2.34) indicates that there are two mechanical points, when \( \omega_A = 0 \) and \( \omega_B = 0 \), they can be expressed as Eq. (2.36):

\[
\frac{\omega_i}{\omega_o} = \frac{\alpha - 1}{\alpha} , \frac{\beta - 1}{\beta}
\]

(2.36)

### 2.2.2 Classification of Planetary Device

According to the connection location difference between the power source, vehicle and EVT, the parallel-series hybrid vehicles with EVT could be classified as Input-split Mode, Output-split Mode, Compound-split Mode and Combinations of Modes. The general model for parallel-series hybrid vehicle is shown in Fig. 2.50. Specifies the output node connected to the vehicle as the reference point (0 point), then the distance from the input to the output node is 1, the distance from the motor MG1 to the output node is \( \alpha \), and the distance from the motor MG2 to the output node is \( \beta \). If \( \alpha \) and \( \beta \) are negative, that’s to say motor MG1 and MG2 are below the base point, if these values are positive they are above the base point.

(1) Input-split Mode

When \( \alpha = 0 \) or \( \beta = 0 \), it is the input-split hybrid system. Such as THS system of Prius and the AHS system in its low speed mode, as shown in Fig. 2.51.

(2) Output-split Mode

When \( \alpha = 1 \) or \( \beta = 1 \), it is the output-split hybrid system. In this mode, when the vehicle is driven the electric power always exist in the system, resulting in the lower efficiency, so this mode is not adopted so far.
(3) Compound-split Mode

When $\alpha \neq 0$ or $\beta \neq 0$, at the same time $\alpha \neq 1$ or $\beta \neq 1$, it is a four-node system like THS-II system of Toyota Lexus GS450h.

(4) Combinations of Modes

A combination of two or three of the above modes. Such as Allison EP-40/50 transmission (Fig. 2.52), when the front planetary row (Ravigneaux planetary gear set) is in the high load drive mode (when the vehicle starting-up) the clutch 1 is separated, the clutch 2 is engaged, and the power system is in input-split mode; when under the low load (cruise mode), clutch 1 is engaged, clutch 2 is separated, the system is in compound-split mode.
2.2.3 Characteristics of Each Mode

2.2.3.1 Characteristics Analysis for Input Power-Split Hybrid System

For an input power-split mode hybrid system, there should be $\beta = 0$, the configuration diagram is shown in Fig. 2.53.

Equation (2.34) can be simplified to Eq. (2.37).

$$
\begin{align*}
\omega_A &= a\omega_i + (1 - a)\omega_o \\
\omega_B &= \omega_o \\
T_i &= -ax_T \\
T_o &= (1 - a)x_T + T_B
\end{align*}
$$

Equation (2.34) can be simplified to Eq. (2.37).

In the definition $r_n = \frac{\omega_o}{\omega_i} / \frac{z-1}{z}$, $r_n$ is obtained by dividing the ratio of EVT to the mechanical point. It’s obvious that when $r_n = 1$, EVT reaches the mechanical point where the system has the highest efficiency. For electric motor MG1, the following equation can be obtained:

$$
\begin{align*}
\frac{\omega_A}{\omega_i} &= a\left(1 - \frac{1}{r_n}\right) \\
\frac{T_A}{T_i} &= \frac{-1}{x} \\
P_{A_{elec/eng}} &= \frac{\omega_A}{\omega_i} \frac{T_A}{T_i} = \frac{1-r_n}{r_n}
\end{align*}
$$

Fig. 2.53 Simplified diagram of the input power-split mode
Assuming that \( T_{AWA} = T_{BW_B} \) (the battery does not work), there is Eq. (2.39) for electric motor MG2.

\[
\frac{\omega_B}{\omega_i} = \frac{x}{x-1} \cdot \frac{1}{r_n}
\]

\[
\frac{T_B}{T_i} = \frac{x-1}{x} (r_n - 1)
\]

\[
P_B_{\text{elec/eng}} = \frac{\omega_B}{\omega_i} \frac{T_B}{T_i} = - \frac{\omega_A}{\omega_i} \frac{T_A}{T_i} = \frac{r_n - 1}{r_n}
\] (2.39)

According to Eqs. (2.38) and (2.39), the static characteristics curves of an input power-split hybrid system are shown as Fig. 2.54. Where, horizontal axis stands for \( r_n \), the vertical axis is the ratio of motor MG1 and MG2 relative to engine speed, torque and power.

From Fig. 2.54, when vehicle velocity is zero, \( r_n \to \infty \), along with the increase of vehicle velocity, \( r_n \) is reducing to 1 and finally smaller than 1, that leads the power ratio increase rapidly and the system efficiency reduces rapidly. In addition, with the increase of planetary structural parameter \( (K_i = R_i/S_i) \), \( x \) also slowly increases, rotary speed of MG1 and torque of MG2 that relative to the engine will larger and larger. There are also some references define structural parameter as \( \rho = S/R_i \), this will have no influence on the statics analysis results [23, 24].

Above all, the conclusion is that this kind of hybrid system need a drive motor MG2 with a large torque and MG1 with wide speed range to choose a mechanical point speed ratio to coordinate the drive-line efficiency and motor size.

2.2.3.2 Characteristics Analysis of Compound Power-Split Hybrid System

First, configuration diagram of compound power-split hybrid system is shown in Fig. 2.55.

Fig. 2.54 Input power-split mode static characteristics curves of hybrid power system
The static Eq. (2.40) of the compound-split hybrid system can be obtained by Eq. (2.34):

\[
\begin{align*}
\frac{\omega_A}{\omega_n} &= \alpha \left(1 - \frac{1}{r_n}\right) \\
\frac{\omega_B}{\omega_n} &= \beta + \frac{\alpha(1-\beta)}{\alpha - 1} \frac{1}{r_n} \\
\frac{T_A}{T_i} &= \frac{\alpha - \beta + \beta(\alpha - 1)(r_n - 1)}{-\alpha(\alpha - \beta)} \\
\frac{T_B}{T_i} &= \frac{(\alpha - 1)(r_n - 1)}{(\alpha - \beta)}
\end{align*}
\] (2.40)

If the range of EVT ratio is defined as \(\Phi\), then we can get \(\Phi\) from Eq. (2.41):

\[
\Phi = \frac{\alpha(\beta - 1)}{\beta(\alpha - 1)}
\] (2.41)

Next, choosing two examples which are the wide ratio range in which \(\alpha = 2, \beta = 0.1, \Phi = 4\) and the narrow ratio range in which \(\alpha = 4, \beta = 0.2, \Phi = 2\), to explain the static characteristics of compound-split hybrid system. Taking \(\alpha\) and \(\beta\) into Eq. (2.40), the static characteristics curves are shown as below:

As can be seen from the static characteristics curves in Fig. 2.56, when velocity of vehicle is zero, \(r_n \to \infty\), with the increasing of vehicle velocity \(r_n\) will reach the first mechanical point (while \(\alpha = 2, \beta = 1\), the first mechanical point is \(r_n = 2\), while \(\alpha = 4, \beta = 2\), the first mechanical point is \(r_n = 1.5\)), between the two mechanical points, the ratio of electric power is smaller, the system efficiency is higher. Similarly, when the ratio of the EVT is greater than the ratio of the second mechanical point, with the increasing of vehicle velocity, the system efficiency will decrease for the reducing of electric power ratio. If the power of motor is negative, it’s generating, if the power of motor is positive, it’s driving.

The conclusion is that the dual-mode compound power-split hybrid system has advantages to be applied to high speed cruising cycles (in low load); its disadvantage is not suitable for low speed starting (in high load). Especially when the vehicle is starting but engine speed is high, the ratio of electric power in electric path is much bigger than 1, which leads to lower overall efficiency of the EVT.
2.2.3.3 Characteristics Analyses of Combinations of Input/Compound Power-Split Hybrid System

Taking the AHS combination power-split mode hybrid system used in America GM Yukon vehicle as example. AHS system is in input power-split mode in low speed (high load), and in compound-split mode in high speed (low load). The static characteristics analysis on AHS system in these two working conditions would be conducted next.

At low speed, the lever model of AHS static characteristics analysis is shown in Fig. 2.57.

![Fig. 2.56 Compound-split static characteristics curves of hybrid power system, when $\alpha = 2$, $\beta = 1$ and $\alpha = 4$, $\beta = 2$](image)

![Fig. 2.57 General lever analysis model of AHS system](image)
According to the load balance and relations of speed, the following equation can be obtained:

\[
(T_A + T_B + T_i)(c + 1) = T_o \\
(a + b)T_A + bT_i = 0 \\
\omega_B = (c + 1)\omega_o \\
\omega_i = \frac{b}{a + b} \omega_A + \frac{a}{a + b} \omega_B
\]  

Eq. (2.42)

If the ratio of EVT is defined as \( R_n \equiv \frac{\omega_i}{\omega_o} \), then Eq. (2.42) can be transferred to Eq. (2.43).

\[
\frac{\omega_A}{\omega_i} = \frac{(a + b)}{b} \frac{a(c + 1)}{R_n} \\
\frac{\omega_B}{\omega_i} = \frac{(c + 1)}{R_n} \\
\frac{T_A}{T_i} = \frac{a^2}{a + b} \left( R_n - 1 \right) \\
\frac{T_B}{T_i} = \frac{b^2}{a + b} \left( \frac{a(c + 1)}{R_n} \right)
\]

Eq. (2.43)

At high speed, AHS system is a compound power-split hybrid system consist of two planetary gears. Analyzing its static characteristics need calculate \( \alpha \) and \( \beta \) in this system, which is shown as Fig. 2.58.

It’s obvious that when the two planetary gears make a compound gear set, \( n_{R2} \) and \( n_{S2} \) in the left diagram in Fig. 2.58 could get from the speed relations between connect points, which is \( n_{R2} = \frac{n_{R2}}{n_{S1} + n_{R1}} \), \( n_{S2} = \frac{n_{S2}}{n_{S1} + n_{R1}} \). To make qualitative analysis, assuming that \( n_{R1} = 9, n_{S2} = 3, n_{R2} = 8 \) and \( n_{S2} = 4 \), correspond to the connect relations of power sources and nodes we get that: \( \alpha = 4/5, \beta = 8/5 \).

Fig. 2.58  Lever analysis model of compound power-split hybrid system
Similarly, use \( R_n \) to take place of \( r_n \) in Eqs. (2.42) and (2.44) is shown as below:

\[
\begin{align*}
\frac{\omega_A}{\omega_i} &= \alpha + \frac{(1-\alpha)}{R_n} \\
\frac{\omega_B}{\omega_i} &= \beta + \frac{(1-\beta)}{R_n} \\
\frac{T_A}{T_i} &= \frac{x-\beta + \beta(\alpha-1)(\frac{x}{R_n}-1)}{-x(\alpha-\beta)} \\
\frac{T_B}{T_i} &= \frac{(x-1)(\frac{x}{R_n}-1)}{x-\beta}
\end{align*}
\] (2.44)

The following conclusions can be obtained by substituting \( \alpha = 4/5 \) and \( \beta = 8/5 \) into Eqs. (2.43) and (2.44) respectively: for low speed condition, mechanical point is \( R_n = 9/4 \), for mid-high speed condition, the two mechanical points are \( R_{n1} = 9/4 \) and \( R_{n2} = 3/8 \). The statics characteristics curves of this double-mode system (AHS) is conducted from Eqs. (2.43) and (2.44), which are shown as Fig. 2.59.

When the rotary speed of motor MG1 is 0, that is at the mechanical point of input power-split and low speed mode and high speed mode convert to each other. As can be seen from Fig. 2.59, during the process \( R_n \) changing from \( \infty \) to 9/4 (in the low speed condition and high load) it takes full advantages of the input-split model: to maintain the power of the vehicle; to avoid the shortcomings of the inefficient transmission system of the compound power-split hybrid system at low speed. During the process \( R_n \) changing from 9/4 to 3/8 (in the high speed condition and low load), it leverages the advantages of the compound power-split mode EVT to drive the vehicle and improve the fuel economy.

### 2.2.4 Summary

The basic principle of the planetary hybrid power-split system is introduced through the static characteristic analysis of model of the hybrid system. Then, based on the

![Fig. 2.59 Static characteristics curves of dual-mode combined hybrid system (AHS)](image-url)
above power splitting modes of the EVT hybrid vehicle, the general model of the series-parallel hybrid system is established by the lever model analysis method. Finally, the characteristics of various configurations and the working characteristics of the system are introduced.

### 2.3 Differential-Based Hybrid System

In order to provide a new kind of power-split device for series-parallel hybrid vehicle, at the same time, to break the shackles of THS power-split device patent of Toyota corporation, through the research and analysis of the structure and working principle of conventional bevel gear differential, as well as the cooperation to PSD of THS system in Prius hybrid vehicle of Toyota corporation, we obtain the feasibility of using traditional differential as the power-split device for series-parallel hybrid vehicle. This new type of system is called Differential-based Hybrid System (DHS) [25]. In this Section, DHS system is compared with THS system in two aspects: the connection and the mechanical properties. Also, the feasibility of this system is proved theoretically.

#### 2.3.1 Comparison of Powertrain Connection

The connection and the mechanical properties of THS system in Prius hybrid vehicle have already been described in detail in the previous article. So, in this part, the connection of DHS system is mainly introduced.

As shown in Fig. 2.60, differential is regarded as the power-split device for hybrid vehicle. Compared with the structure of system I, system II is connected by a single speed ratio gear between the generator and the left axle. The speed ratio can be determined in accordance with the speed relationship between the rotating speed or the torque relationship between the engines.

![Fig. 2.60 Differential-based hybrid system](image-url)
The connection relationship of the three-ends of differential and power source is: left side gear is connected with generator; driven bevel gear is connected with engine; right side gear is connected with motor.

Because the differential power-split device and THS-PSD both belong to 2 K-H structure (as shown in Fig. 2.61), i.e. the two forms are the same in structural connection, it is unnecessary to redesign the overall structure, which proves the feasibility in connection. The traditional differential power-split device changes the three-end speed and torque ratio of DHS, but it can be adjusted with a single ratio gear. So, besides the two structural forms described above, the single speed ratio gear may also be arranged between the engine and the driven gear or the right side gear of DHS and drive motor.

### 2.3.2 Relationship Between Speed and Torque

In THS and DHS system, speed relationship between the power sources can both be expressed as:

\[ k_1 w_g = kw_m = (1 + k)w_e \]  

For THS system, \( k = z_r / z_s = 2.6 \), \( k_1 = 1 \). For DHS system, \( k = 1 \), \( k_1 = 1 \).

As shown in Fig. 2.62, according to Eq. (2.45) and Fig. 2.60, the relationship between the speed of each power source of powertrain structure and the vehicle velocity can be obtained. Among them, the relationship between the speed of the three main power components (generator, drive motor and engine) is:

\[ w_y + w_m = 2 \cdot w_e \]  

The relationship between the driving motor speed and vehicle velocity is:

\[ w_m = 35.11 \cdot v \]  

As shown in Fig. 2.63, according to Eq. (2.46) and Eq. (2.47), the restrictive relationship between the power sources can be obtained.
Substituting the Eq. (2.45) into the energy conservation equation, the torque relationship of DHS system can be obtained [26–28]:

\[
T_{\text{left gear}} = T_{\text{right gear}} = kT_e/(1 + k)
\]

\[
T_g/k_1 = T_e/(1 + k)
\]

where \( T_{\text{right gear}} \) is torque of DHS right side gear. For THS system, \( k = z_r/z_s = 2.6, k_1 = 1 \). For DHS system, \( k = 1, k_1 = 1 \).

Since the size of the motor is proportional to the maximum torque, the first configuration requires a slightly larger generator than the Prius. If the gear ratio of the second configuration is 3.6/2, according to the torque relationship, the size of its generator can be the same with the generator in Prius.

It can be seen from the speed relationship, compared with the THS-PSD, the DHS not only does not limit the best performance of the engine when the speed of generator is high during vehicle is accelerating, it also provides more convenience.
for powertrain assembly matching. This shows that the differential is feasible as a power coupling device in terms of structure.

2.3.3 Summary

By deeply analyzing the structure and working principle of traditional differential and contrasting it with mature products of Prius THS, it can be seen that the traditional differential as a dynamic coupling device can fully meet the dynamic coupling requirements of hybrid vehicles. Therefore, the differential as a power-split power coupling system for HEV is not only feasible, but also can be a new dynamic coupling system.

2.4 Summary

In this chapter, the typical configurations of planetary hybrid system in the market, including the THS system of Toyota and the AHS system of GM, are introduced. On this basis, the working principle and analysis method of planetary hybrid system are discussed. Characteristic analyses of each mode, including input power-split, compound power-split and combinations of input/compound power-splits hybrid system, are conducted. In the end, the connection and mechanical properties of DHS systems are analyzed, and the feasibility of this DHS is discussed.

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