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Configuration Synthesis of Novel Series-Parallel Hybrid Transmission Systems with Eight-Link Ravigneaux Mechanisms

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Keywords: hybrid electric vehicles, configuration synthesis, planetary gear train (PGT), Ravigneaux, eight-link mechanism.

ABSTRACT

Hybrid electric vehicle (HEV) has been invented and developed over the past two decades. It is the promising solution for cutting down emission and reducing pollution besides electric vehicles. Since a series hybrid vehicle needs no transmission, the transmissions of parallel and series-parallel hybrid systems are studied nowadays. This paper presents a design approach for the configuration synthesis of series-parallel hybrid transmissions with the eight-link Ravigneaux mechanisms. The synthesis process subject to the concluded design consist of 7 mechanisms with eight members and twelve joints including the combination of two planetary gear trains. Then, by using the techniques of power and clutch arrangements, new series-parallel hybrid transmissions are synthesized with 27 clutchless hybrid systems and 27 corresponding series-parallel hybrid transmissions. A new hybrid transmission is selected as an example to demonstrate the feasibility of the synthesized configurations by analyzing the working principle with operation modes and power flow paths.

INTRODUCTION

To inherit the advantages of series and parallel models, series-parallel hybrid transmission systems are proposed to optimize fuel efficiency and drivability based on the operating conditions of vehicles.

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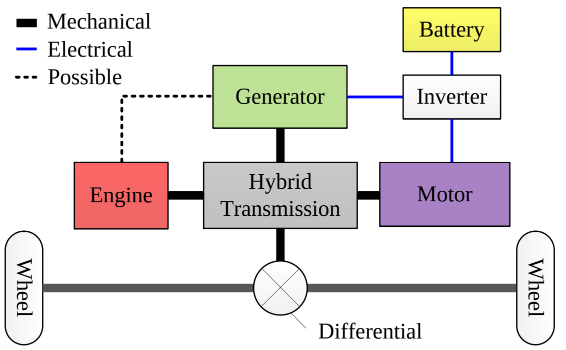

Fig. 1. Configuration of a typical series-parallel HEV.

Fig. 1 shows the configuration of a series-parallel system. In comparison to a series system, the engine is coupled to the final drive through a hybrid transmission to drive the wheels directly. As compared to a parallel system, the series-parallel system has a separated generator.

Ever since the first concept of hybrid vehicles was introduced, many concepts for hybrid transmissions have been developed [1-10]. Toyota Prius, the first hybrid vehicle by using the hybrid configuration, was successfully introduced to the US market in the 2000s and is called hybrid synergy drive (HSD) [11-13]. Toyota then improved HSD design by a mechanism with two degrees of freedom (2-DoF) and one or two simple planetary gear trains (PGTs) without any clutch in the transmission [14-15]. As a result, HSD is a configuration that is difficult for controlling series operation modes.

In 1996, GM developed their hybrid transmission, a popular design among hybrid vehicles. It uses a two-mode hybrid transmission with the combination two PGTs with two clutches and one brake [16-18], for running at both high speed and low speed. The clutches and brakes are engaged to control many flexible operation modes and improve both vehicle performance and fuel economy [19]. In addition, many companies such as Honda, Renault, Nissan, Hyundai and KIA also came out their designs of hybrid vehicles [20-22].

Many hybrid transmissions have been designed and analyzed based on traditional automatic transmissions, and there are some transmission configurations using the Ragvineaux mechanism [23, 24]. With the extension of Yan's methodology for the systematic generation of new feasible configurations for HEVs [25, 26], Ngo and Yan synthesized feasible configurations of series-parallel hybrid transmissions with seven members and ten joints [27]. Based on such a method, this work proposes an approach for the configuration synthesis of novel series- parallel hybrid transmissions with eight-link Ragvineaux mechanisms, Fig. 2.

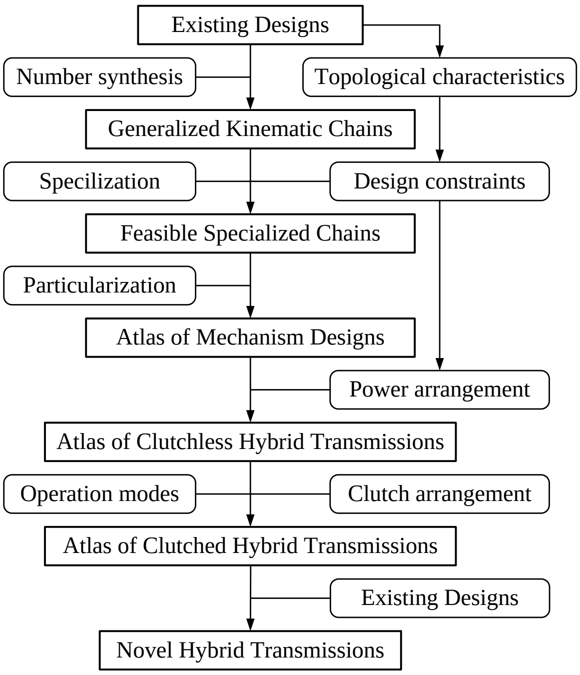

Fig. 2. Procedure of configuration synthesis.

EXISTING HYBRID TRANSMISSIONS

The first step is to identify the existing design of the Ravigneaux mechanism with eight links and twelve joints [23]. And, Fig. 3(a) and 3(b) show the schematic diagrams and the corresponding generalized kinematic chain (GKC), respectively.

Topological characteristics

By analyzing this existing design, its topological characteristics are concluded as follows:

1. It is a Ravigneaux mechanism with 2-DoF, which is a combination of two PGTs.
2. It has eight members including one ground link (member 1), two sun gears (members 2 and 3), one carrier (member 4), two planetary gears (members 5 and 6) and two ring gears (members 7 and 8).
3. It has twelve joints, consisting of seven revolute joints (J_R) and five gear joints (J_G) including three external gear joints (J_G^o) and two internal gear joints (J_G^i).
4. It has five links adjacent to the ground link.

A planetary gear train with 2-DoF must satisfy the following expressions [25]:

$$N_J = 2N_L - 4, \tag{1}$$

$$N_{JR} = N_L - 1, \tag{2}$$

$$N_{JG} = N_L - 3, \tag{3}$$

where, N_J, N_{JR}, N_{JG}, and N_L denote the numbers of joints, revolute joints, gear joints, and members, respectively.

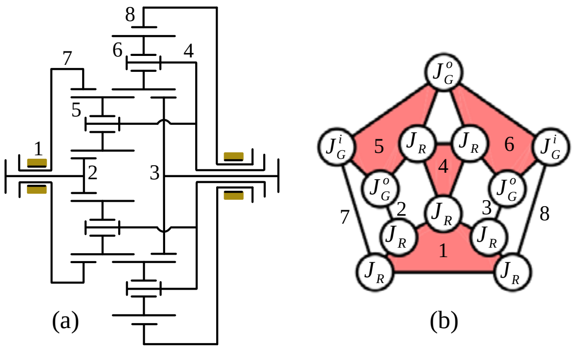

Fig. 3. Transmission with eight-link Ravigneaux mechanism:
(a) Schematic diagram; (b) Corresponding GKC.

Operation modes

Six basic operation modes of a series-parallel hybrid system based on the vehicle operating conditions are presented by Mi et al. [19] to show how the system works and what the status of each input and output source. And, they are concluded as follows:

1. Motor alone mode: At high level, the battery provides energy to the motor that alone drives the vehicle.
2. Engine alone mode: when the power demand is middle (e.g., during highway cruising control), the engine alone mode is turned on to further improve fuel efficiency.
3. Combined power mode: the engine is turned on together with the motor to provide additional power to drive the vehicle when the power demand or required for heavy load or high-speed acceleration.
4. Power split mode: when the power demand is low but the engine still turns on, partial of engine power drives the vehicle and the remaining

engine power is converted into electricity to charge the battery by the motor or generator.

5. Regenerative braking mode: the electric motor and by the motor or generator is operated to convert kinetic energy from the vehicle's braking process into electrical energy, which charges in the battery.
6. Stationary charging mode: when the vehicle is at a standstill and the battery is low, the engine drives the generator to charge the battery.

Series-parallel hybrid systems inherit the advantages of both series and parallel systems leading to optimize fuel efficiency and drivability based on the operating conditions of vehicles.

Based on the analysis of the existing design, the operation characteristics of the output and the inputs including the engine, the motor and the generator at each operation mode, are concluded. In most hybrid systems, two couples (motor and output, and engine and generator) are located on the same simple PGT. In addition, since the motor speed is high and high torque is needed to move the vehicle in electric vehicle mode (motor alone mode), the motor speed transmitted to the output shaft must be reduced to provide high torque to the output shaft at low vehicle speed. Similarly, the generator normally works at the higher speed than that of the engine, and thus the speed of the engine is equal to or lower than the speed of the generator when the simple PGT is of 1-DoF. These characteristics are useful for concluding of the design constraints of inputs/output locations in a new system.

GENERALIZED KINEMATIC CHAINS

The process of generalization transforms the schematic diagram of existing design, which includes various types of members and joints, into its corresponding GKC based on a set of generalization rules [25]. For the Ravigneaux mechanism shown in Fig. 3(a), the generalization process is carried out as follows, Fig. 3(b):

1. Since the fixed ground link (member 1) is adjacent to five members (members 2, 3, 4, 7 and 8) by five revolute joints, it is generalized into quinary link 1 (a link with five joints).
2. Since the sun gear (member 2) is adjacent to one planetary gear (member 5) and the ground link (member 1), it is generalized into binary link 2 (a link with two joints).
3. Since the sun gear (member 3) is adjacent to one planetary gear (member 6) and the ground link (member 1), it is generalized into binary link 3.
4. Since carrier (member 4) is adjacent to two planetary gears (members 5 and 6) and the ground link (member 1), it is generalized into ternary link 4 (a link with three joints).
5. Since the planet gear (member 5) is adjacent to three gears (members 2, 6 and 7) and the carrier (member 4), it is generalized into quaternary link 5 (a link with four joints).
6. Since the planet gear (member 6) is adjacent to three gears (members 3, 5 and 8) and the carrier (member 4), it is generalized into quaternary link 6.
7. Since the ring gear (member 7) is adjacent to a planet gear (member 5) and the ground link (member 1), it is generalized into binary link 7.
8. Since the ring gear (member 8) is adjacent to a planet gear (member 6) and the ground link (member 1), it is generalized into binary link 8.

The corresponding GKC shown in Fig. 3(b) has eight generalized links and twelve generalized joints. According to the number synthesis of GKCs, there are 406 GKCs for mechanisms with eight members and twelve joints [25].

SPECIALIZED CHAINS

Feasible specialized chains are identified from GKCs subject to design constraints.

Mechanism constraints

Ground link (member 1):

1. There must be one fixed link as the ground link.
2. The ground link must be at least a quaternary link adjacent to binary links.

Carrier (member 4):

The carrier (member 4) is adjacent to all planet gears (members 5 and 6) and the ground link (member 1)

Planet gear (members 5 and 6):

1. A planet gear must not be adjacent to the ground link.
2. There is no three-bar loop formed by any link adjacent to a planet gear, a binary link, and the ground link.
3. Each planet gear must have just one carrier.

Sun and ring gears (members 2, 3, 7 and 8):

1. There must be at least one sun (ring) gear in a PGT.
2. The sun (ring) gear must be adjacent to both the ground link and a planet gear.

Revolute joint (J_R):

1. There must be seven revolute joints.
2. The joints between a planet gear and its carrier, the ground link and a binary link must be revolute joints.

Gear pair (J_G):

1. There must be five gear joints, including three external gear joints (J_G^o) and two internal gear joints (J_G^i).
2. The joint between a planet gear and a ring (sun) gear must be a gear joint.

Inputs/output constraints

Output (O)

1. One member of compound PGT must be connected to the output shaft.
2. The output must be connected to a ring gear or planetary carrier of a PGT in order to achieve high torque transfer when the motor drives the vehicle alone.
3. The output and the motor must be on the same PGT set, and can adjacent to each other.
4. In the PGT set, the motor speed must be faster than the speed of the output shaft if the third link is fixed.

Motor (M)
1. One member of compound PGT must be connected to the motor shaft.
2. The motor must be connected to a ring gear or a sun gear in order to achieve speed reduction and obtain higher torque at the output shaft.
3. The motor must not be connected to a carrier in order to avoid excessive output speed.

Generator (G)
1. One member of compound PGT must be connected to the generator shaft.
2. The generator must be at least connected to a sun gear or a ring gear in order to achieve high speed during braking and regeneration.

Engine (E)
1. One member of compound PGT must be connected to the engine shaft.
2. The engine must be at least connected to a ring gear or planetary carrier in order to have high efficiency when the vehicle is at high speed.
3. The engine and the generator must be on the same PGT set, and can adjacent to each other.
4. In the PGT set, the generator speed must be faster than the speed of the engine when the third link is fixed.

Feasible Specialized Chains

Specialization is the process of assigning specific types of members and joints into the Atlas of GKCs obtained above, subject to concluded design constraints. And a specialized chain subject to design constraints is called a feasible specialized chain [25].

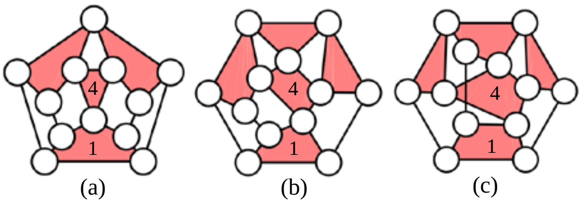

Fig. 4. Specialized chains with identified ground link and the carrier of the Ravigneaux mechanism.

From the 406 available GKCs obtained above, only three GKCs with eight links and twelve joints satisfy the constraints of the ground link and the carrier of the Ravigneaux mechanism, as shown in Fig. 4. The corresponding feasible specialized chains subject to the design constraints above are identified according to the following steps:

Step 1: Assign the ground link (member 1). For each GKC, the ground link is assigned, as shown in Fig. 4.

Step 2: Assign the carrier of the double PGT. For each result in Step 1, the carrier of the Ravigneaux mechanism is assigned, as shown in Fig. 4.

Steps 3, 4 and 5: Assign the planetary gear(s), the sun (ring) gear and the remaining member(s). For each result in Step 2, the planet gear(s) and the sun (ring) gear are assigned. At the end of this step, the remaining member(s) are also assigned, as shown in Fig. 5(c3) to (c6).

Step 6: Assign the revolute joints (J_R). For each result in Step 5, the revolute joints are assigned. Four results are generated, as shown in Fig. 5(c7) to (c10).

Step 7: Assign the gear joints (J_G). For each result in Step 6, the two external and two internal gear joints (J_G^o and J_G^i) are assigned. As a result, four specialized chains are generated, as shown in Fig. 5(c11) to (c14).

Step 8: Transfer specialized chains to block diagrams. For each result in Step 7, four specialized chains are transferred to their corresponding block diagrams, as shown in Fig. 5(c15) to (c18).

Step 9: Transfer block diagrams to schematic diagrams. For each result in Step 8, four block diagrams are transferred to their corresponding schematic diagrams, as shown in Fig. 5(c19) to (c22).

By using this process, the GKCs are shown in Fig. 4(c) generate four corresponding feasible specialized chains, as shown in Fig. 5.

Atlas of Mechanism Designs

Particularization, the reverse graphical process of generalization, is used to regenerate corresponding schematic diagrams of the obtained feasible specialized chains [25]. Each feasible specialized chain obtained above is converted into its corresponding block diagram, as shown in Figure 6. And, there are 7 feasible specialized chains transferring into 7 block diagrams and 7 schematic diagrams, respectively. In addition, Fig. 6(a7) and 6(b7) show the original Ravigneaux mechanism.

ATLAS OF CLUTCHLESS AND CLUTCHED HYBRID TRANSMISSIONS

Now, power arrangement, clutch arrangement, and operation modes are considered.

Power arrangement

This is the power arrangement process that aims to assign the inputs and output to the obtained mechanisms. The mechanisms are shown in Fig. 6(a1) is taken as an example to illustrate this process.

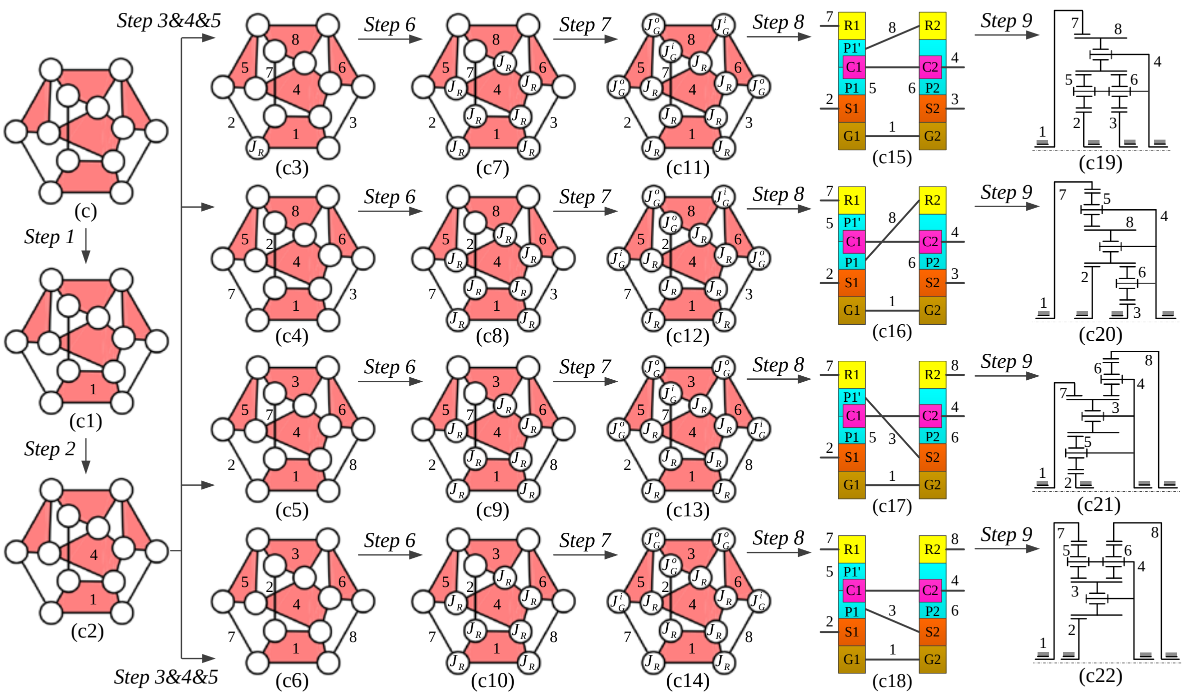

Fig. 5. Process of specialization.

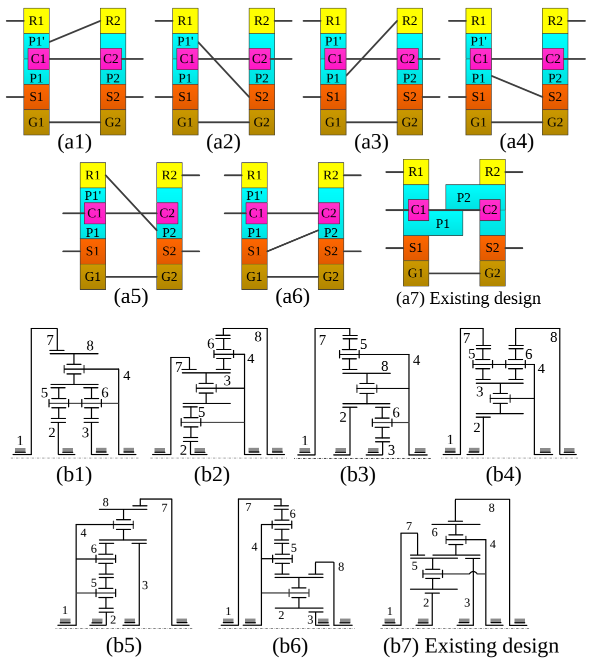

Fig. 6. Atlas of eight-link Ravigneaux mechanism for hybrid transmission.

Based on the design constraints for the inputs/output, the engine, motor, generator, and output are assigned to each mechanism according to the following steps:

Step 1: Assign the Output (O). For this mechanism, the generator is assigned. Two results are generated, as shown in Fig. 7(1.1) to (1.2).

Step 2: Assign the Motor (M). For each result in Step 1, the motor is assigned. The assignment of the engine generates three results, as shown in Fig. 7(1.3) to (1.5).

Step 3 and Step 4: Assign the Engine (E) and the Generator (G). For each result in Step 2, the engine and the generator are assigned to generate four results, as shown in Fig. 7(1.6) to (1.9).

By applying this process to the other mechanisms, 27 systems with the identified generator, engine, motor, and output are generated corresponding to the 7 obtained mechanisms. And, Fig. 8 shows the Atlas of hybrid transmission systems without clutch and brake.

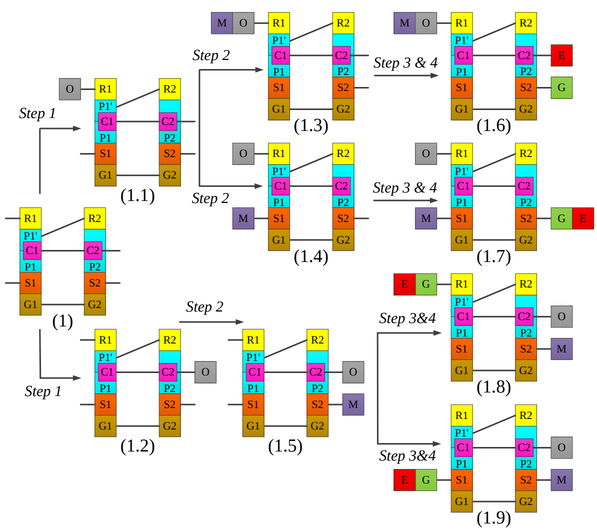

Fig. 7. Process of power arrangement.
E: engine; M: motor; G: generator; O: output shaft.

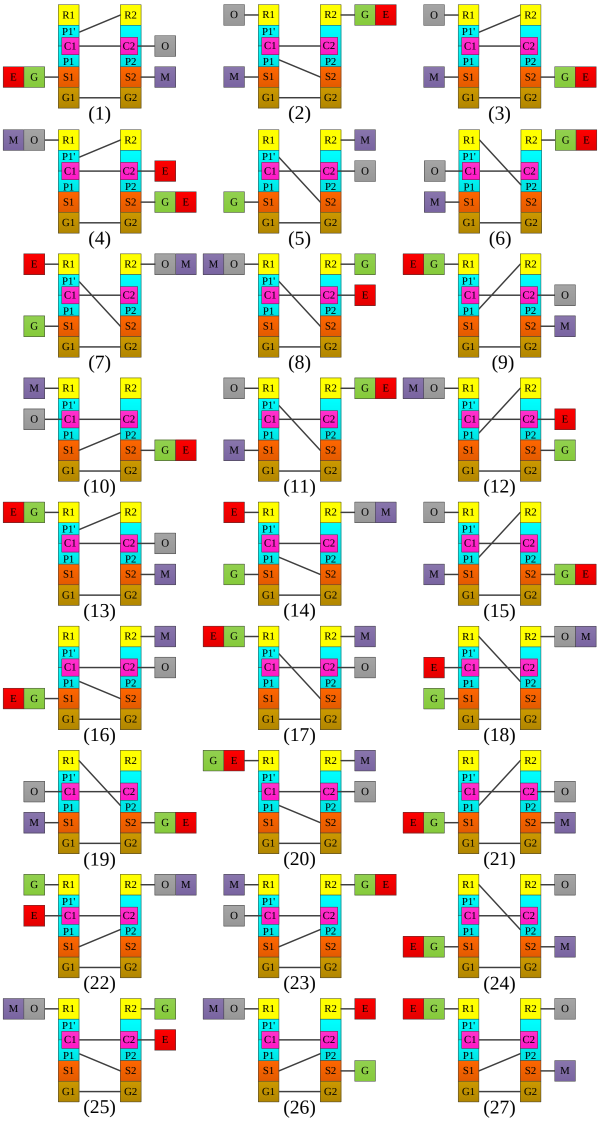

Fig. 8. Atlas of hybrid transmission systems without clutch.

Clutch arrangement

Clutch arrangement is the process of assigning clutches and brakes to a system to control its operation modes subject to the required operation modes. It includes two main steps: the required operation modes and clutch arrangement.

a. Required operation modes

Since the purpose of this work is to develop new series-parallel hybrid transmission systems, the operation modes of new systems are listed in Table 1. The characteristics of power sources and the output are based on the operation modes presented above.

b. Clutch arrangement

Based on the operation modes and status of power sources in each mode, the following process is used to add clutches and brakes to each system to achieve the required operation modes with the minimal number of clutches and brakes. The system is shown in Fig. 8(2) and (6) are taken as examples to illustrate the clutch arrangement process, as shown in Fig. 9, respectively.

Step 1: Series HEV (hybrid electric vehicle) mode. In series mode, the engine cannot be connected to the output shaft, and thus the common link(s) that connects the two PGTs must be separated into two independent PGTs by the clutch (CL). In addition, if a PGT is a 2-DoF mechanism, a brake must be added, making it a 1-DoF design. The addition of clutches and brakes generates two results, as shown in Fig. 9(2.1) and (6.1). These systems can also operate under one motor alone, regenerative braking, and engine start condition (electric vehicle mode).

Step 2: Parallel HEV mode. In parallel mode, the engine can be connected to the output shaft, and thus the systems become 2-DoF, the brakes are released, and the clutches are engaged to connect the two PGTs. No more clutches or brakes are added, as shown in Fig. 9(2.2) and (6.2). These systems can also operate under combined power or power split condition, as in CVT mode.

Step 3: Engine alone mode. Since engine drive mode is required, the system is operated as 1-DoF system while the engine drives the vehicle. The addition of clutches and brakes generates two results, as shown in Fig. 9(2.3) and (6.3).

By applying this process to all systems, 27 clutched systems are synthesized for series-parallel hybrid transmissions, as shown in Fig. 10.

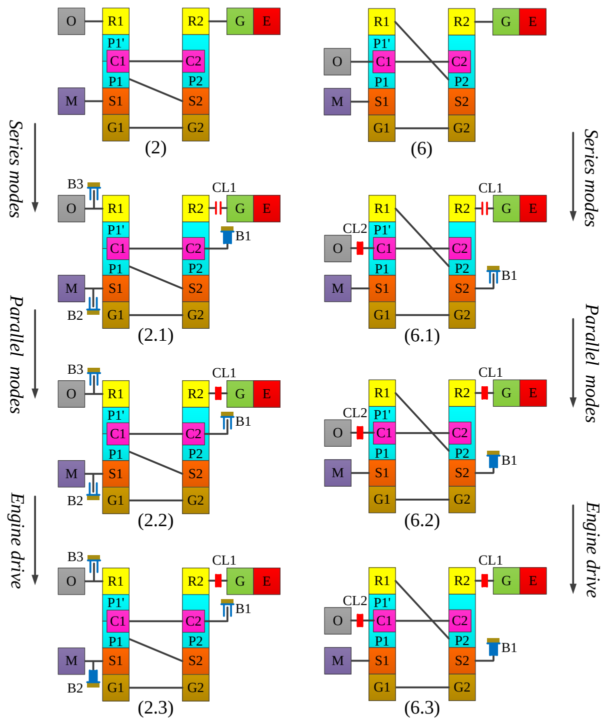

Fig. 9. Process of clutch arrangement.

Table 1. Proposed operation modes of a new series-parallel hybrid system.

No.	Operation mode	System degrees of freedom	Power sources	Remark
1	Motor alone	1	M	M drives the vehicle
2	Series	1	M, E, G	M drives the vehicle, while E drives G
3	Engine start	1	M, G	M drives the vehicle, while G starts E
4	Engine alone	1	E	E alone drives the vehicle with M (and G) idling
5	Combined power	1 or 2	E, M	E and M (and G) drive the vehicle
6	Split power (CVT)	1 or 2	E	E power is split with one part driving the vehicle and the other driving M (and G)
7	Regenerative braking	1	Output	M works as a generator

E: engine, M: motor, G: generator, O: output shaft, CVT: continuously variable transmission.

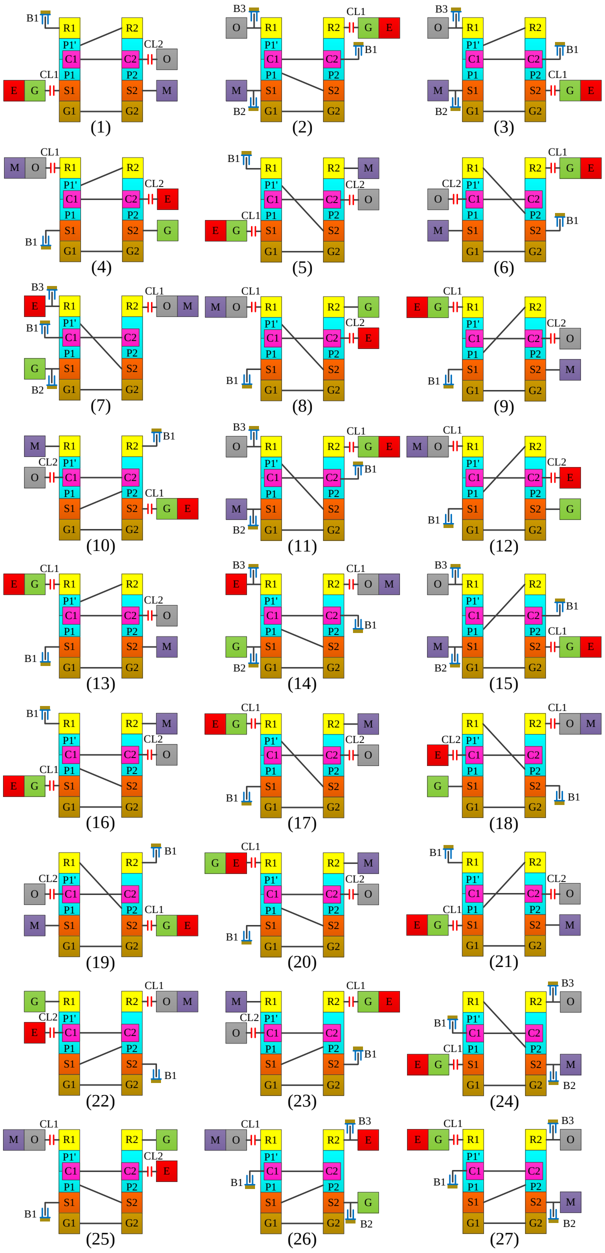

Fig. 10. Atlas of series-parallel hybrid transmissions. E: engine; M: motor; G: generator; O: output shaft; CL: clutch; B: brake.

ANALYSIS OF A NEW SERIES-PARALLEL HYBRID TRANSMISSION

To demonstrate the feasibility of the synthesized hybrid transmissions, the design is shown in Fig. 10(14) is selected as an example to show the operation modes and power flow analysis of the new system, Fig. 11. The operation modes are shown in Fig. 12, are divided into twelve possible clutching conditions as listed in Table 2, where an “x” indicates that the corresponding brake or clutch is engaged.

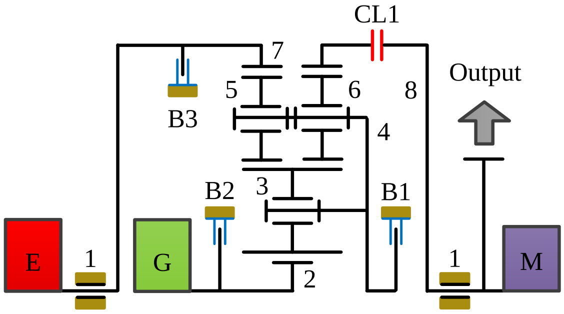

Fig. 11. A novel series-parallel hybrid transmission.

The relationship presented for torque and power provides the reference values of the power in each operation mode. Then based on the power demand of the vehicle in a particular operation, the suitable operation mode is selected. Furthermore, with more clutches and brakes added to the systems, more operation modes can be performed to provide flexible control method for HEVs during operation to further improve fuel economy.

Table 2. Operation modes and clutching conditions.

No.	Operation mode	Clutch and brake engagement				Remark
		CL1	B1	B2	B3	
1	Motor alone					M alone drives the vehicle, while E idles
2	Series		x			M drives the vehicle, while E drives G
3	Engine start		x			M drives the vehicle, while G starts E
4	Engine alone	x		x		E alone drives the vehicle with M (and G) idling
5	Combined power	x		x		E and M (and G) drive the vehicle
6	Split power 1	x				E power is split with one part driving the vehicle and the other driving M (and G)
7	Split power 2	x		x		
8	Split power 3	x				
9	Regenerative braking 1					
10	Regenerative braking 2	x			x	M work as a generator
11	Regenerative braking 3	x			x	
12	Stationary charging		x			E drives G

E: engine, M: motor, G: generator, O: output shaft, CL: clutch number, B: brake

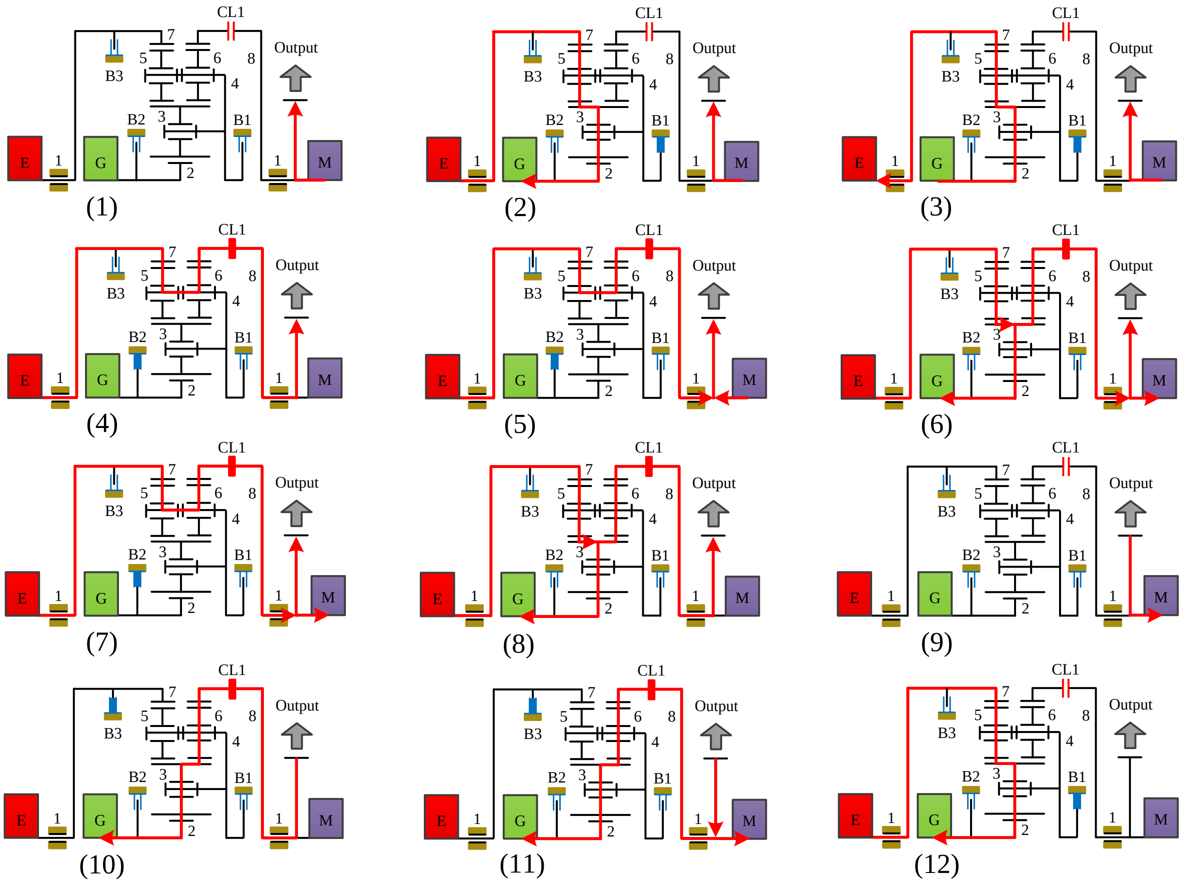

Fig. 12. Operation modes of the novel series-parallel hybrid transmission.

CONCLUSIONS

A design procedure is proposed and illustrated based on the extension of the creative mechanism design methodology to synthesize the feasible mechanisms for the configurations of hybrid transmissions. Then, by using the techniques of power arrangement and clutch arrangement, the mechanisms are used for synthesizing clutchless and clutched hybrid transmissions. As a result, 7 compound PGTs are systematically synthesized for hybrid transmission by using the creative design techniques, 27 clutchless and 27 clutched series-parallel hybrid transmissions are synthesized.

The design constraints and desired operation modes decide the number of mechanisms and hybrid transmissions. Since some of the operation modes are required and some of them are flexible choices of engineers, systems with different characteristics can be generated.

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八桿 Ravigneaux 式串並聯混合動力傳動系統之構形設計

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摘 要

在過去的二十年間，混合動力車(HEV)正在被大量的研發，並被認為是電動車之外最具節能及降低汙染排放的交通工具，非常具有前景。對於各種傳動系統的研究而言，由於串聯式的動力混合並不需要傳動系統，因此並聯式及串並聯混合式的傳動系統則成了現今的研究焦點。本研究針對具八桿 Ravigneaux 式機構合成串並聯混合動力傳動系統進行分析及研究。其中，透過創意性機構設計方法，有系統的整合出七種具有 8 桿 12 接頭，包含兩組行星齒輪之可應用之傳動機構。再藉由動力源及離合器之配置技術，分別合成出 27 種串並聯式及 27 種離合器混合傳動機構。最後，為了證明本研究提出方法及合成系統的可行性，從中選擇一種新型混合動力傳動機構為例，說明工作原理、操作模式、與功流分析。