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Comparison of multi-mode hybrid powertrains with multiple planetary gears

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HIGHLIGHTS

- Double and triple-planetary-gear power-split hybrid powertrains are compared.
- Fuel efficiency is optimized by a near-optimal control strategy.
- Passenger cars adopts two-planetary-gear powertrain for cost consideration.
- Triple-planetary-gear powertrain provides higher output torque.
- Triple-planetary-gear powertrain is appropriate for SUVs, pick-up trucks or buses.

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ABSTRACT

Most hybrid electric vehicles (HEVs) currently sold are power-split HEVs that use single, double or occasionally even multiple planetary gear (PG) sets to connect their powertrain elements. Adding PG sets can provide more design flexibility; however, it also increases system complexity and cost. This paper presents a comparative study of hybrid powertrains with different numbers of PG sets, which we term configurations. The analysis of different configuration types is investigated both qualitatively and quantitatively. In the qualitative analysis, the performances of operating modes for different configurations are compared, in terms of mode number, normalized efficiency, and maximum output torque. The quantitative approach compares the designs of different configurations; the fuel economy and acceleration performance of all superior designs are evaluated to make the comparison iconic. The results show that triple-PG hybrids do not have significant fuel economy improvement compared with double-PG hybrids, but they achieve a dramatic improvement in acceleration performance; this can be beneficial for sport utility vehicles (SUVs), light trucks, and buses. For cost consideration, it is suggested that passenger cars adopt double-PG hybrid powertrains.

1. Introduction

Hybrid electric vehicles (HEVs) are considered as a promising technology in the future, as the corporate average fuel economy (CAFÉ) standards become more strict [1], and public environmental awareness rises.

Recent studies have improved the fuel efficiency of HEVs by optimizing control strategy [2–5] and component sizes [6]. Another aspect, configuration, is also important for realization of a fuel-efficient powertrain. Series, parallel, and power-split configurations are three typical HEV types in the market. Among all the three types, the power-split type which uses planetary gear (PG) sets has dominant market shares because it has better fuel economy performance than the other two HEV types [7]. With a PG system and two motor/generators (MGs), the engine speed can be decoupled from the vehicle speed to realize the electric continuous variable transmission (ECVT) function.

The single-PG configuration is the most compact and economical structure to realize ECVT. The best-selling HEVs on the market, such as the Toyota Prius, Chevrolet Volt, and Ford Fusion Hybrid, all began with a single-PG structure [8]. Researchers recently explored all possible designs for single-PG hybrids by

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developing methodologies to model all topologies automatically. Zhang et al. proposed a new multi-mode HEV that improves fuel economy considerably by adding an extra clutch to the Toyota Prius [9]. Bayrak et al. drew the same conclusion by applying the bond graph technique to model all feasible designs with a single PG [10]. In addition to searching structures, Kang et al. also considered the final drive and PG ratios as design variables. The best single PG design with an optimized gear ratio was identified through a systematic search [11].

In recent years, engineers and researchers have shifted their interest to HEVs with multiple PGs [12]. Because double-PG hybrids appear to have better performance than single-PG hybrids, two currently popular HEVs, the Toyota Prius and Chevrolet Volt, were both changed to double-PG designs in 2010 [9] and 2015 [13,14], respectively. In addition to these two vehicles, other powertrains using two PGs were released or patented [15–18]. Most double-PG powertrains are equipped with clutches to enable multiple operating modes. By switching clutch states, different operating modes can be achieved in the same powertrain.

The availability of multiple modes enables a system to achieve high fuel efficiency and drivability in varied driving conditions such as city driving and highway cruising. For example, ECVT modes have better efficiency in city driving [19], where parallel modes provide higher torque when higher acceleration or towing capability is required. The GM Allison Hybrid System (AHS) is a typical double-PG transmission originally developed for hybrid buses and heavy-duty vehicles [18]. It has two operating modes, input-split mode and compound-split mode, which enable the system to operate efficiently in both low- and high-torque ranges. Identifying the optimal double-PG design became possible after Zhang et al. developed an automated modeling method [20].

Furthermore, some original equipment manufacturers have even proposed hybrid designs with three PGs recently. The GM two-mode hybrid is a typical three-PG transmission [16]. "Two mode" means that two different mode types, ECVT modes and parallel modes, are combined in one hybrid powertrain. Two types of modes in one powertrain can satisfy torque demands for high acceleration, hill climbing and towing, while maintaining high efficiency in normal driving scenarios.

Previous studies have attempted to identify the best designs for single- or double-PG hybrid powertrains that are referred to as different configurations in subsequent discussions. However, the fuel economy benefit of having more than two PGs in one powertrain system remains unclear. In this paper, we compare the performance of two configurations, double-PG and triple-PG hybrids in both qualitative and quantitative ways. In the qualitative analysis, the functions of HEVs, i.e., their operating modes, are examined and compared for both double-PG and triple-PG configurations. In the quantitative analysis, we model all designs with no more than three clutches, and then compare these configurations from a performance perspective. Finally, the benefits of triple-PG hybrid powertrains are discussed.

The remainder of this paper is organized as follows: In Section 2, the automatic modeling of power-split powertrains is introduced. This method is employed to build the models of all modes for both double- and triple-PG hybrids in Section 3. These two configuration types are compared in terms of total mode number and performance. Section 4 compares the performance of all designs of these two configuration types using three clutches. Finally, conclusions are presented in Section 5.

2. System dynamics and automatic modeling

Multi-mode HEVs can be realized by adding clutches to a PG system. A clutch can be added either between two PG nodes, or between a PG node and the vehicle body frame (grounding clutch). The total number of possible clutches can be calculated by Eq. (1), where N_p is the number of PG sets.

$$N_{clutch} = C_{3N_p}^{2} + 3N_p - 2N_p - 1 \quad (1)$$

In Eq. (1), the first term represents the clutches added between each pair of nodes; the second term represents grounding clutches. Since locking any two of the three nodes in one PG produces identical dynamics, such redundant clutches are eliminated by the third term. In addition, the output shaft should not be grounded. Therefore, the total numbers of clutches for double- and triple-PG configurations are 16 and 38, respectively, according to Eq. (1). All possible clutch locations for these systems are displayed in Fig. 1, where invalid clutches are marked in red. Note that for each specific design, if all selected modes use the same engaged clutch, that clutch can be replaced by permanent connections, which incur little cost or operation complexity.

A methodology to model the modes of multi-mode HEVs was proposed in [21]. The dynamics of any specific mode is described by the characteristic matrix A^*, as shown in Eq. (2). This 4×4 characteristic matrix A^* governs the relationship between the angular acceleration of powertrain devices and their corresponding torques. The detailed derivation can be found in [21].

$$\begin{bmatrix} \dot{\omega}_{out} \\ \dot{\omega}_{eng} \\ \dot{\omega}_{MG1} \\ \dot{\omega}_{MG2} \end{bmatrix} = A^* \begin{bmatrix} T_{load} \\ T_{eng} \\ T_{MG1} \\ T_{MG2} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{31} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} T_{load} \\ T_{eng} \\ T_{MG1} \\ T_{MG2} \end{bmatrix}. \quad (2)$$

3. Qualitative comparison

The performance of a multi-mode HEV is decided by its operating modes. The modes with high efficiency will likely result in a fuel-saving hybrid design. In this section, we will compare double-PG hybrids with triple-PG hybrids from the perspective of mode number and mode performance, respectively.

Before deriving all modes of double- and triple-PG hybrids, we first need to decide the locations of powertrain components. In theory, the four powertrain components (engine, two MGs, and the output shaft) can connect to any PG node. To make a fair comparison, we fix the powertrain locations as shown in Fig. 2; i.e., the engine connects the ring gear of the first PG, the output shaft is at the carrier gear of the last PG, and MG1 and MG2 connect with the sun gears of first and last PGs, respectively.

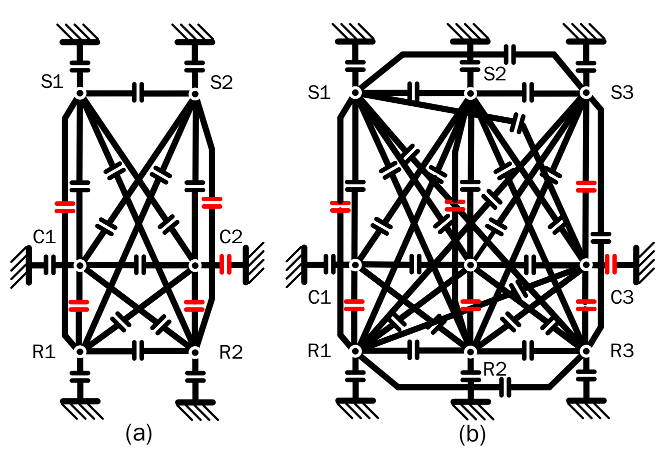

Fig. 1. All possible clutch locations for double-PG and triple-PG hybrids.