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Comparison of power-split and parallel hybrid powertrain architectures with a single electric machine: Dynamic programming approach

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HIGHLIGHTS

- A power-split HEV with a single electric motor is constructed.
- Comparisons with P1 and P2 hybrid systems are made.
- Dynamic programming optimizes the hybrid systems.
- Multiple operating modes are useful to fuel economy.

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ABSTRACT

Due to limited flexibility of engine operation, it is uneasy to improve the fuel economy of parallel hybrid electric vehicles (HEVs) with a single electric machine (SEM) from control perspective only. However, from design perspective, it is likely to devise multiple operating modes on a powertrain system to achieve better fuel economy. Therefore, in this paper, a velocity coupling HEV system with a SEM has been proposed, which has eleven modes, including an electric vehicle (EV) mode, three regenerative braking modes, an engine-start mode, an electrically variable transmission (EVT) mode, a parallel HEV mode, an engine-only mode, and three charging modes. Dynamic Programming (DP), as a global optimization algorithm, is leveraged to minimize the fuel consumption of this system. For comparison purposes, the P1 and P2 HEV systems are also examined by DP using the same vehicular parameters. Comparative results indicate that the P2 HEV saves about 6.68% fuel consumption over the P1 HEV, while more improvement can be observed from the proposed velocity coupling HEV, with 13.82% fuel consumption reduction over the P1 HEV.

1. Introduction

Hybrid electric vehicles (HEVs) are among the most promising solutions to overcome serious concerns over environmental deterioration and fuel shortage [1–5]. Almost all automotive companies are actively developing HEVs [6–8]. Among all HEV types, power-split HEVs are the most popular type, as they can achieve great fuel economy with the electrically variable transmission (EVT) function which decouples the engine speed from the vehicle speed [9]. For example, Zhang et al. have developed systematic design procedures with automated modeling and screening for power-split HEVs [10,11]. Nevertheless, these EVT systems need two electric machines, which are very complicated and expensive [12]. In contrast, HEVs with a single electric machine (SEM) are more cost-competitive and efficient [13]. Therefore, increasing researchers have been exploring them. Their salient characteristic is to obtain excellent fuel economy and emissions reduction through several operating modes, e.g., idle-stop mode, motor assisting mode, charging mode, and regenerative braking mode [14–17]. Munan et al. demonstrated that an HEV with a SEM improved 2.27% fuel economy by using idle-stop only in NEDC cycle and 6% in NEDC when using both idle-stop and motor assisting modes [18]. Malikopoulos et al. found that a high-mobility multi-wheel vehicle (HMMWV) with a SEM decreased 4.3% fuel economy in city-highway combined cycle [19]. Liao et al. showed that a hybrid truck with a SEM increased about 13% fuel economy, compared to the conventional truck on primary road conditions [20].

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Depending on different positions of the SEM, there are 5 types of configurations, as illustrated in Fig. 1, including P0 (belt driven starter/generator), P1 (SEM mounted on crankshaft), P2 (SEM mounted on the gearbox input), P3 (SEM mounted on the gearbox output), and P4 (SEM mounted on the driving axle). For instance, Chevrolet Malibu and Toyota crown hybrids used the P0 architecture. The P1 system was applied to many vehicles as well, such as Honda insight (IMA system) and Chevrolet Silverado. Hyundai and Infinite M35 adopted the P2 system. BYD developed a P3-type HEV.

Many researchers have focused on increasing fuel economy of HEVs with a SEM. Sundström et al. performed a comparative study of the P1 and P2 systems via Dynamic Programming (DP). The result concluded that the P2 has a better fuel economy [21]. Koot et al. conducted a comparative examination between the P1 and P2 systems via linear programming (LP), concluding that the P2 system is advantageous [22]. In spite of these, the fact that the engine and SEM rotate on the same shaft makes the assistance of SEM in the P2 system to the engine limited.

To further enhance fuel economy, researchers have been recently studying EVT systems. Such systems can better decouple the engine and motor, and have more operating modes, leading to higher fuel efficiency. Because of the reduced number of motors, EVT systems with a SEM exhibit lower power loss, lower production cost, and more compact architecture over EVT systems with two EMs. Zhu et al. presented the mathematical modeling and analysis of a novel EVT system with a SEM for a hybrid bus [23]. Simulation under the NEDC cycle showed that the fuel consumption of EVT system with a SEM is comparable to a benchmark vehicle, an EVT system with two EMs and no clutch. However, the proposed architecture by Zhu et al. used two planetary gear (PG) sets and four clutches, resulting in higher production cost and system complexity, in contrast to single-PG EVT systems with fewer clutches.

EVT systems with two EMs, e.g., Toyota Hybrid System (THS-II) and GM-Allision (AHS), generally employ two or more PG sets with high production cost and architecture complexity. The EVT system with a SEM developed in [23] still utilizes two PG sets. Zhang and Lin [24] proposed an EVT system with a SEM and studied its performance using Simulink/Advisor platform. A significant improvement in fuel economy was observed in diverse cycles, compared with the configuration used by Toyota Prius.

This paper deals with a velocity coupling HEV system with a SEM, as sketched in Fig. 2, which aims to assist the engine in operating in the highest-efficiency region to maximize fuel economy. Since this system merely needs a SEM, a single PG set, and two clutches, it is more cost-competitive and simpler than most of the foregoing EVT systems. The devised architecture leverages two clutches including a one-way clutch and a wet multi-disk clutch. The one-way clutch can eliminate engine drag in EV mode and/or regenerative braking, which diminishes fuel consumption and engine wear. Thanks to a PG set, this hybrid system can realize the EVT mode, which enables the engine to operate in the highest-efficiency region and to obtain excellent fuel economy.

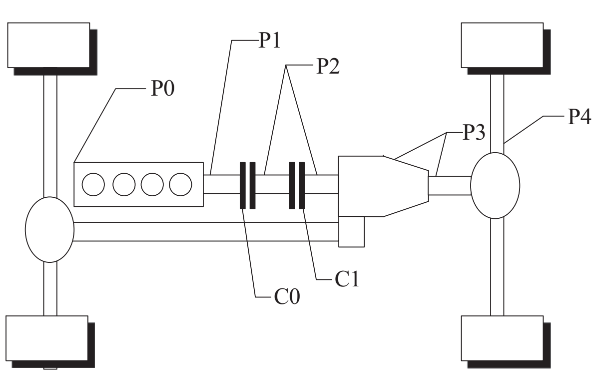

Fig. 1. Configurations of HEVs with a SEM.

Although comparative studies between EVT systems with two EMs and parallel HEVs were carried out [25–27], to the best of our knowledge, there is a shortage of a comparative study between EVT with a SEM and parallel HEVs. The primary goal of the article is to bridge this gap. Specifically, globally DP-based optimal energy management strategy is exploited to compare three architectures, i.e., the proposed system, P1 system, and P2 system, in terms of maximum fuel-saving potential.

The remainder of the paper proceeds as follows. Section 2 describes the operating modes of the proposed system and vehicle parameters. The powertrain modeling is detailed in Section 3. The DP-based energy management problem is formulated in Section 4. Simulation results, discussion, and comparative analysis are provided in Section 5. Important conclusions are ultimately summarized in Section 6.

2. Operating modes and vehicle parameters

The velocity coupling system with a SEM has eleven modes through engaging/disengaging a wet clutch and/or a one-way clutch, as shown in Table 1.

As shown in Fig. 3, the PG set consists of a sun gear, a carrier and a ring gear. According to the PG kinematic equation

$$S\omega_r + R\omega_s = (R+S)\omega_c, \tag{1}$$

when the wet clutch is engaged, all speeds of the three PG nodes become the same, namely,

$$\omega_r = \omega_s = \omega_c. \tag{2}$$

Then, the system operates as a parallel HEV mode. When the wet clutch is disengaged, the system operates as an EVT mode, which is beneficial to increase the operating efficiency of engine. When operating in EV or regenerative braking, the system can eliminate engine drag by coordinated control of the one-way clutch and the wet multi-disk clutch. As a result, the overall efficiency of the system can be improved. All of these constitute salient advantages over P1 and P2 systems.

According to our prior effort [28], dynamic equations of the EVT mode are depicted in the matrix form by

$$\begin{bmatrix} I_e + I_r & 0 & 0 & R \\ 0 & I_c + \frac{R_w^2}{i_g^2 i_o^2} m & 0 & -(R+S) \\ 0 & 0 & I_m + I_s & S \\ R & -(R+S) & S & 0 \end{bmatrix} \begin{bmatrix} \dot{\omega}_e \\ \dot{\omega}_o \\ \dot{\omega}_m \\ F \end{bmatrix} = \begin{bmatrix} T_e \\ -T_f \\ T_m \\ 0 \end{bmatrix} \tag{3}$$

where I_e, I_r, I_c, I_s, and I_m are inertias of the engine, ring gear, carrier, sun gear, and motor, respectively. Furthermore, i_g is gear ratio, and i_o is final ratio. The wheel radius is denoted by R_w, m is vehicle mass, ω_e, ω_o, and ω_m are angular speeds of the engine, output (carrier), and motor, respectively. The internal force between the pinion gears and other gears are represented by F, T_e, T_f, and T_m are torques of the engine, friction braking, and motor, respectively.

The main vehicle parameters are listed in Table 2, which are applied to all the three configurations to be examined.