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Modeling, control, and performance of a novel architecture of hybrid electric powertrain system

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HIGHLIGHTS

- Novel hybrid electric powertrain is proposed and its performance analyzed.
- The architecture allows for efficient active torque suppression.
- Physics-based models are easily resized.
- A multi-state power management strategy is designed for system power efficiency.
- A fuel economy assessment method is proposed to save computational cost.

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ABSTRACT

Hybrid electric vehicles (HEVs) have become increasingly popular due to their high fuel economy performance. HEVs typically fall into three categories according to their powertrain configuration, namely serial, parallel, and power-split hybrid. All these configurations use small internal combustion engines (ICEs), which can suffer from high torque fluctuations detrimental for noise, vibration and harshness performance. This paper introduces a novel architecture of hybrid electric powertrain systems (patent pending) which suppresses torque fluctuations and carries out the functionality of hybrid driving. This new hybrid architecture conceptually lies between a serial and a power-split. The new system uses an ICE and two electric machines, including one with a rotating stator, and has the functionalities of existing hybrid powertrains, including transmission, boost, regenerative braking. The paper presents a model for this new powertrain, and a unique controller implemented in MATLAB Simulink®. A specially designed ruled-based multi-state controller is included in the model to achieve control and enhance fuel economy. Results of drive cycle simulations show the systems performance including torque fluctuation suppression and great fuel economy.

1. Introduction

With the purpose of reducing emissions and improving fuel economy, policies on vehicle fuel consumption and emission have been set up around the world. This has triggered significant new developments in hybrid vehicles over the last two decades [1]. Hybrid vehicles use more than one type of power source. Among all combinations of available power sources, an internal combustion engine (ICE) plus an electric battery system that drives one or more electric motors/generators is the most popular. This combination of power sources are used in hybrid electric vehicles (HEVs). Typical configurations of HEV powertrains fall into three categories, namely series, parallel, and power-split. Studies of such architectures have been carried out recently [2–10] with most focusing on power-split hybrids. Other, more limited research focuses on series and parallel hybrids [11,12]. Related studies for commercial HEV powertrains have been done by Chan [13], and Wu et al. [14].

To study HEVs, models of powertrain architectures are needed. These include modeling methods and tools for powertrains, system dynamics, and emissions. For example, Kim et al. have designed a novel multi-mode parallel HEV powertrain and assessed its fuel economy. Multi-mode operation is realized by planetary gears

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[15] and by engaging or disengaging different power sources. For example, Zhu et al. have designed a HEV powertrain with a single electric machine and two planetary gears [16]. Millo et al. developed models and a prototype for an urban hybrid bus [17]. Bougrine et al. applied a chemistry-based method and simulated CO and NO emissions models [18]. Also, several researchers have developed modeling tool for HEV architectures with embedded rule-based controllers [19].

Control and optimization are also needed for designing HEVs of different topologies, including control and power management of single powertrains and of multi-mode powertrains, and optimization of fuel economy and emissions. Al-Aawar and Arkadan have designed an optimal control strategy which maximizes fuel economy by using a mathematical search algorithm, and maximizes drivability by using a fuzzy logic algorithm [20]. Hou et al. have developed a control strategy based on estimating trip information acquired using statistical methods [21]. Other approaches use game theory controllers developed by Dextreit et al. Their time-independent control strategy manages power by judging the cost of fuel consumption, emissions, and battery SOC [22]. In 2014, Finesso et al. designed and optimized a diesel parallel hybrid powertrain [23]. Torres et al. developed an optimal power management strategy for plug-in hybrid electric vehicles [24]. In contrast, Lee and Kim successfully created a controller of continuously variable transmission (CVT) ratio to improve parallel HEVs [25].

Dynamic programming is often used in control and optimization because it can guarantee global optimality under certain conditions. However, dynamic programming is not a real-time control strategy, and its computational cost is high. To address these challenges, Kum et al. have developed a real-time optimal power and catalyst management strategy for plug-in HEV and parallel HEV based on studying the characteristics of dynamic programming results [26,27]. Zhang et al. have proposed a real-time control strategy that selects the most power efficient mode of a multi-mode HEV powertrain to achieve near-optimal fuel-economy [28]. A similar method is described in Shabbir and Evangelous work [29], Other control strategies on multi-mode HEVs are found in the work of Zhang et al. [30], Borhan et al. [31], Ahn and Papalambros [32], Katrašnik [33], and Lin et al. [34], among others.

With given devices, a given (typically large) number of possible powertrain topologies exist. It is of great interest to finding which of these topologies are best, namely maximize for some utility function such as fuel economy. Zhang et al. have developed an exhaustive search methodology for optimal designs for topologies with given power sources and planetary gear sets and clutches [35]. Mohan et al. have designed a framework with similar functionality, but using a systematic search method which compares all possible topologies simultaneously [36]. Silvas et al. have designed an automatic HEV topology generator which generates feasible topologies using given power sources and transmission components [37].

Since the ICE is not their only power source, typical HEVs use smaller ICEs with fewer cylinders compared to conventional vehicles. Such ICEs suffer from higher torque fluctuations which lower the noise, vibration, and harshness (NVH) performance. Mechanically dampening torque fluctuations is one way to enhance NVH performance. However, the energy loss in such approaches can be large, and that can affect the efficiency of the powertrain. Previous studies of NVH in HEV powertrains focus mostly on vibrations which occur during the transient period upon mode shifting, clutch engaging or disengaging [38–40]. The novel powertrain architecture studied in this paper uses electric power to suppress torque and power fluctuations without additional damping, which saves energy.

The powertrain system analyzed in this paper takes advantage of a specialized electric machine which has a stator that is allowed to rotate. This machine is connected to the ICE (which unavoidably exhibits torque fluctuations) and to another, conventional electric machine. Having a rotating stator enables the first machine to adjust the angular velocity in the powertrain downstream of the ICE. The conventional machine controls the torque transmitted to the wheels, and also suppresses torque fluctuations caused by the ICE. This new architecture does not fall into any of the three existing HEV configurations, but is viewed as between a series and a power-split.

To evaluate the performance of the new powertrain architecture, a vehicle-level model is created. This includes a two-level control strategy which sets the ICE operating point and distributes power to the electric machines. The controller uses an event-based strategy where events represent changes in driving conditions.

The vehicle-level model and its control were implemented in Matlab Simulink® with separate models for the powertrain and vehicle components, namely: simplified ICE model, model of the battery system, models of the power electronics, models of the electric machines and their regulators, model of vehicle dynamics including driver. The control strategy was implemented into two controllers. The component models and controllers were connected to obtain a vehicle-level model. Each component of the model was tested individually. Also, tests were carried out to verify the functionality of the powertrain system and vehicle-level model. These tests include single and multiple drive cycles, which monitor the functionality of individual devices and components, and the power sustaining of the powertrain system over relatively long times of driving.

2. Hybrid powertrain structure overview

This section introduces the new hybrid powertrain architecture, including its structure and operating modes.

This hybrid powertrain system consists of an ICE, two electric machines (motors/generators) with their regulators, a battery, and necessary mechanical connections. Existing HEV powertrain designs typically use planetary gears and clutches [41]. However, planetary gears and clutches are not necessary in our design. This change sacrifices the multiple configuration possibilities, but enhances the reliability of the powertrain. The two electric machines are referred to as the A and B machines. The configuration of the powertrain is shown in Fig. 1. The ICE block is mounted on the frame of the vehicle. The crank shaft (rotor) of the ICE is connected to the A rotor. The A stator can rotate, and is connected to the B rotor, which is further connected to the wheels and may include a gear with a fixed ratio. The B stator is mounted on the vehicle frame.

The crank shaft angular velocity is denoted by ω_E and the angular velocity of the A rotor by ω_{AR}. When the shaft connecting the ICE and the A rotor is rigid, $\omega_{AR} = \omega_E$. The angular velocity of the A stator is denoted by ω_{AS} and the angular velocity of the B rotor is denoted by ω_B. When the shaft connecting the A rotor to the B rotor is rigid, $\omega_{AS} = \omega_B$. Also, the angular velocity of the rotating components which are upstream of the final drive but downstream of the B machine is denoted by ω_d. When the shaft connecting the B rotor to the final drive is rigid, $\omega_d = \omega_B$. The angular velocity of the wheels is denoted by ω_w. The final drive ratio can be expressed as $r_f = \omega_d/\omega_w$, and thus the vehicle speed is $v = r_w\omega_w = r_w(\omega_d/r_f)$, where r_w is the wheel radius.

Note that neither the stator nor the rotor of the A machine is fixed. The A rotor has an angular velocity of ω_{AR} whereas the A stator has an angular velocity of ω_{AS}. Thus, the A machine is able to provide a difference between the angular velocities ω_E of the crank shaft and the angular velocity ω_B of the B rotor. We refer to the relative angular velocity between the rotor and the stator of the A