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Hardware-in-the-loop simulation for the design and verification of the control system of a series–parallel hybrid electric city-bus

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ABSTRACT

Hybrid electric buses have been a promising technology to dramatically lower fuel consumption and carbon dioxide (CO_2) emission, while energy management strategy (EMS) is a critical technology to the improvements in fuel economy for hybrid electric vehicles (HEVs). In this paper, a suboptimal EMS is developed for the real-time control of a series–parallel hybrid electric bus. It is then investigated and verified in a hardware-in-the-loop (HIL) simulation system constructed on PT-LABCAR, a commercial real-time simulator. First, an optimal EMS is obtained via iterative dynamic programming (IDP) by defining a cost function over a specific drive cycle to minimize fuel consumption, as well as to achieve zero battery state-of-charge (SOC) change and to avoid frequent clutch operation. The IDP method can lower the computational burden and improve the accuracy. Second, the suboptimal EMS for real-time control is developed by constructing an Elman neural network (NN) based on the aforementioned optimal EMS, so the real-time suboptimal EMS can be used in the vehicle control unit (VCU) of the hybrid bus. The real VCU is investigated and verified utilizing a HIL simulator in a virtual forward-facing HEV environment consisting of vehicle, driver and driving environment. The simulation results demonstrate that the proposed real-time suboptimal EMS by the neural network can coordinate the overall hybrid powertrain of the hybrid bus to optimize fuel economy over different drive cycles, and the given drive cycles can be tracked while sustaining the battery SOC level.

1. Introduction

Hybrid electric vehicles (HEVs) represent an effective approach to reducing fuel consumption and alleviating global warming, as they can improve fuel efficiency and emit less carbon dioxide (CO_2) [1–3]. As for the heavy-duty vehicles with high fuel consumption, such as city buses, the reductions in fuel consumption and emissions due to hybridization are more substantial than those of sedans. Therefore, research on hybrid electric city buses is a crucial step to avoid further global environmental deterioration and further energy shortages.

The improvements in fuel economy and the reductions in emissions of hybrid electric city buses heavily depend upon the energy management strategy (EMS) in vehicle control units (VCUs) [4,5]. EMS can determine the most appropriate drive mode and the most fuel efficient power split between the engine and the motor. Moreover, it optimally exploits the energy storage capacity of the battery and improves engine operating efficiency according to the power request and the vehicle status [6], thereby lowering fuel consumption while maintaining drivability and sustaining the battery state-of-charge (SOC) level. For vehicle hybridization, a series–parallel powertrain configuration, which combines a series hybrid system with a parallel hybrid system, can realize the drive modes of both series and parallel hybrids. Therefore, this system makes

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it easier to lower fuel consumption and emissions than either series or parallel powertrain configurations alone. Thus, series–parallel hybrid buses provide significant advantages in urban traffic conditions, such as an increase in fuel economy and the suitability for a variety of driving conditions. However, the development of a control system for a series–parallel hybrid powertrain is rather difficult, since its architecture and control functions are more complex than those of either series or parallel hybrid types [4,5].

The main challenge of control system development for a series–parallel hybrid system lies in the development of EMS and electronic control units. A trend in EMS development is the introduction of the global optimization method [2,7–15]. Due to the high nonlinearity and the complex interactions of hybrid powertrain components, it is difficult to apply the analytical methods to this optimal control problem [2,16,17]. Thus, numerical algorithms, especially the DP method, have received much attention as an effective approach to obtaining the globally optimal control policy for HEVs [2,7]. There are two types of DP methods used with HEVs: deterministic dynamic programming (DDP) and stochastic dynamic programming (SDP) [2]. Lin and Kum [9,11,13] presented an optimal control strategy design procedure for a parallel HEV by extracting implementable optimal rules from the DDP solutions over a specific drive cycle. The research results demonstrated better performance on fuel economy, emissions and drivability compared to the HEV with the intuition-based algorithms. However, the extraction method, which includes drive modes pre-definition, DDP solutions classification, and curve fit, is very complex and time-consuming. In addition, Liu, Lin and Johannesson conducted studies on SDP for HEV EMS designs. They modeled the power request from driver as a random Markov process, and stored the obtained full state-based optimal control laws (Liu and Lin) or cost of each state (Johannesson) for real-time implementation [8,10,14]. The SDP solutions are time-invariant and can be directly implemented, thus the SDP method shows significant advantages for the HEV optimization problem. However, the state transition probabilities depend on the drive cycles under consideration. It also must be noted that the control strategy is optimal only for the given Markov chain, thus SDP will lose some optimality compared to DDP for the given drive cycle.

Recently, a great change in the implementation process of new electronic control units is the adoption of HIL simulation [18–22]. A typical characteristic of the HIL simulation for the control unit development is the integration of the real controller with the plant models. The HIL simulation cannot only verify the effectiveness of the control strategy of the ECU, which is newly developed, but also match and optimize its parameters [18]. There have been many studies that have validated the HIL simulation approach as an efficient and reliable tool for control system development and verification. For example, a hybrid electric powertrain ECU development project has been successfully implemented by Ford Motor Company, using the HIL testing system based on the Commercial-Off-The-Shelf dSPACE toolset [20]. In the Ford Motor Company's project, the performance of the ECU was tested in a virtual real-time vehicle environment, which included all the key hybrid electric powertrain components, such as engine, motor, high-voltage battery, transmission, and human driver. The results of the Company's project showed that the ECU development cycle was significantly shortened and the software quality was greatly improved. In addition, a HIL simulation system for the development of the engine management system for the new Mercedes-Benz truck engines was established by researchers at the Technical University of Darmstadt [19]. The HIL system of the Technical University of Darmstadt was used to develop new control functions and to test the software and hardware of the engine electronics [18–22].

Since the HIL simulation method requires less hardware than the fully physical components, and can avoid the difficulty of accurately assessing control functions by desktop simulations, the control system of the proposed series–parallel hybrid bus is developed based on HIL simulation. The EMS, suitable for urban traffic conditions and the specific powertrain configuration, is developed by the IDP approach and Elman neural network (NN) under the given drive cycle. Then, a HIL simulator is built on PT-LABCAR taking into account the real-time requirements and fidelity. In this way, the control functions and performance of the VCU of the series–parallel hybrid bus can be tested and improved.

2. Vehicle control system development

The EMS in the VCU of a HEV is an algorithm to regulate the operation of powertrain to achieve the optimal fuel economy and/or emissions performance over a specific drive cycle, while meeting drivability requirements and sustaining the battery SOC level. Generally, the development of HEV EMS is based on the specific powertrain configuration and drive cycle [1,5,6].

2.1. Powertrain configuration

A series–parallel hybrid electric bus is developed based on the prototype vehicle of a 12 m, 4×2 rear drive transit bus. Basic parameters of the vehicle are listed in Table 1, and the powertrain configuration is shown in Fig. 1.

Table 1
Main specification of the vehicle.

Item	Value
Curb/gross weight (kg)	12200/17000
Wheel base (m)	5.8
Tire rolling radius (m)	0.508
Frontal area (m^2)	7.5
Aerodynamic drag coefficient	0.62