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Hierarchical and Adaptive Neuro-Fuzzy Control for Intelligent Energy Management in Hybrid Electric Vehicles ⋆

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Abstract: This work is concerned with the minimization of total energy consumption (summation of electric battery and fuel) of hybrid hydraulic-electric vehicles through an energy management combined approach incorporating elements of fuzzy logic, neural network and rule-based algorithms. In this paper, the global vehicle effciency is calculated by considering electrical motor, battery, engine, hydraulic pump, hydraulic motor and the transmission. An adaptive fuzzy neural algorithm is embedded in the vehicle with a fuzzy mode-switching control strategy along with proposed fuzzy tuning controllers to achieve real time control. In addition, a new formula is developed to update the proposed fuzzy controller. An intelligent hierarchical hybrid controller strategy is employed with several advantages: (i) proposed strategy does not depend on the a priori knowledge of the driving event, which makes it suitable to be implemented online; (ii) it can be easily implemented in real time based on fuzzy rule-based strategy containing five operation modes; (iii) rate of charge of the battery is limited to minimize aging effects; (iv) engine is operated near its optimal range. The effectiveness of the overall proposed architecture is demonstrated under various conditions in MATLAB/Truckmaker simulations which show increased efficiency over Pontryagin's minimum principle. Offline and online control performance of the proposed approach are tested.

Keywords: Hybrid Electric Vehicle, Power Management Strategy, Hierarchical Control Architecture, Adaptive and Optimal Neuro-Fuzzy Controller.

1. INTRODUCTION

The problem of reducing the environment pollution in order to save the planet has become one of the most important challenges in the world. Besides, the worldwide crisis of the fossil fuel resources, which diminish at high rate, aggravates it. These two global aspects made the big industrial companies and the state governments invest increasingly into the alternative energy sources. The hybrid electric vehicles (HEV) promise a relevant solution with regard to the objectives of reducing the fuel consumption, as well as the decrease of the exhaust gazes emission Murphey (2008). The presence of additional power sources in the HEV introduces additional degrees of freedom in controlling the drivetrain, since at each time the drivers power request can be delivered by either one of the on-board energy sources or their combination. The additional degrees of freedom can be leveraged to reduce fuel consumption and pollutant emissions and also to optimize other possible cost such as battery life Li (2015). This task is performed by the energy management strategy which is the highest control layer of the drivetrains control strategy. Energy management strategies can be divided into numerical and analytical approaches. In numerical optimization methods like dynamic programming Ximing (2015), the global optimum is found numerically under the assumption of full knowledge of the future driving conditions. Unfortunately, the results obtained through dynamic programming cannot be implemented directly due to its high computational demands. To remedy this problem, approximated dynamic programming and stochastic dynamic programming Johannesson (2007), Moura (2011) had been suggested as possible solutions. Analytical optimization methods, on the other hand, use a mathematical problem formulation to find an analytical solution that makes the obtained solution faster than the purely numerical methods. Within this category, Pontryagin's Minimum Principle (PMP) based energy management strategy is introduced as an optimal control solution Panday (2016). This approach can only generate an optimal solution if implemented offline since in this case the driving cycle is supposed to be known in advance. In addition, rule-based strategies developed from heuristic ideas are widely used in HEVs applications Mashadi (2010), Mi (2011), Ying (2016), Kamal (2016) because they can be implemented easily in real-time, but creating these rules commonly requires engineering experience, large numbers of experimental results, etc., and have generally limited benefits for fuel economy. In order to improve the fuel economy of rule-based methods, the authors in Lihao (2016) directly adopted fuzzy rules instead of deterministic ones to improve the operational efficiency

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of vehicle system. In Duan (2003) the authors added a fuzzy algorithm for the rule-based method, to modify the rules. To further reduce fuel consumption, fuzzy controllers were further modified using particle swarm optimization Chen (2015), genetic algorithms Wu (2008), and machine learning algorithms Zhou (2013). Moreover, learning vector quantization using neural network Murphey (2011) or a fuzzy neural network Wu (2012) are used. The integrated fuzzy-neural-network system has the merits of both fuzzy systems Tian (2011) (human-like conditional rules which depend on knowledge of an expert or past experience) and Neural Networks (NN) Wang (1997) (learning and optimization abilities and connectionist structures).

In this work, the design and analysis of a novel Intelligent Hierarchical Hybrid Controller Strategy (IHHCS) for Hybrid Hydraulic-Electric Vehicles (HHEVs) is presented. The primary objective is to develop a practical, reliable and implementable intelligent control strategy, which can manage the power distribution among different energy sources to maximize the hybrid vehicle's overall efficiency. This hybrid strategy minimizes the total energy consumption (summation of electric battery and fuel) and it can be employed for both offline and online scenarios. The proposed strategy consists of three control level based on neural network, fuzzy logic and rule based optimization. An Intelligent Supervisory Switching Mode Controller (ISSMC) based on fuzzy logic in the third level, an Intelligent Power Distribution and Optimization Controller (IPDOC) based on optimal neural fuzzy logic strategy in the second level and Local Fuzzy tuning Proportional-Integral-Derivative Controllers (LFPIDC) in the first level. We compare MATLAB/Truckmaker simulations with alternative frameworks existing in the literature based on PMP Panday (2016) in order to demonstrate the advantages of our methodology.

The results of this paper support that the proposed strategy is capable of: (i) being applied to various types of HEV; (ii) an accurate and reliable model of the studied bus (i.e., BUSINOVA) is design by MATLAB/Truckmaker software; (iii) reducing fuel consumption by optimizing switching control modes; (iv) increasing global vehicle efficiency; (v) being implemented in real-time; (vi) reducing the number of rules needed in fuzzy control; (vii) being used either offline or online; (viii) maintaining the engine near its optimal operating range; (ix) keeping State Of Charge (SOC) within the range which promotes battery longevity.

The paper is organized as follows. The overall HHEVs description and modeling is given in section 2. In section 3, the proposed intelligent hierarchical hybrid controller structure is developed. Simulation results and comparative analysis by MATLAB/Truckmaker simulator are presented in section 4. Finally, the conclusions and future prospects are presented in section 5.

2. MODELING OF THE HYBRID BUS

The aim of this section is to modeling based on Truckmaker software and illustrate the architecture and the mathematical model of the studied system, i.e., BUSINOVA hybrid bus, developed by SAFRA company (cf. Figure 1). This bus is composed of an Electric Motor (EM), a Hydraulic Motor (HM), an Internal Combustion Engine (ICE) and battery as the propulsion powertrain system of the vehicle.

Fig. 1. BUSINOVA hybrid bus.

2.1 Hybrid bus powertrain architecture

The model of the studied hybrid bus is based on a series-parallel power-split hybrid architecture Bayindir (2011). A simple block diagram of the power flows in the bus is shown in Figure 2. The EM and HM are both directly connected to the transmission and can ensure simultaneously or independently the traction of the bus. On the other hand, the ICE is coupled to a Hydraulic Pump (HP) for driving the HM, and therefore allowing the ICE load shifting.

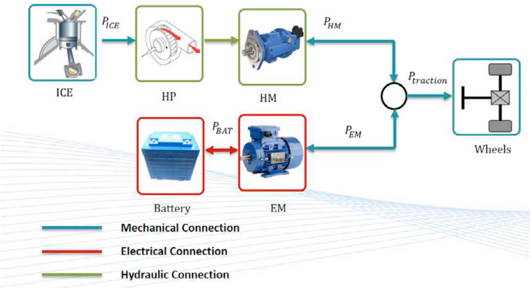

Fig. 2. Block diagram of the powertrain power flows. (ICE: Internal Combustion Engine, HP: Hydraulic Pump, HM: Hydraulic Motor, EM: Electric Motor)

The rotational speeds of the HM and the EM are imposed by the wheels speed in proportion to the reduction ratios of HM and EM respectively. Moreover, the rotational speed ω_{HM} and the torque T_{HM} are expressed as follows:

$$\begin{cases} \omega_{HM}\left(T_{ICE}, D_{HM}\right) = \dfrac{D_{HP}.\eta_{v_{HM}}.\omega_{ICE}}{D_{HM}.\eta_{v_{HP}}} \\ T_{HM}\left(T_{ICE}, D_{HM}\right) = \dfrac{D_{HM}.\eta_{m_{HM}}.T_{ICE}}{D_{HP}.\eta_{m_{HP}}} \end{cases} \tag{1}$$

where ω_{ICE}, T_{ICE} are respectively rotational speed and torque of the ICE, and D_{HM}, D_{HP}, $\eta_{m_{HM}}$, $\eta_{m_{HP}}$, $\eta_{v_{HM}}$, $\eta_{v_{HP}}$ are respectively displacement, mechanical efficiency and volumetric efficiency of the HM and the HP.

The BUSINOVA can operate according to the modes described below:

- the propulsion is fully supplied by the EM (mode 1),
- the bus is actuated by the HM via the ICE (mode 2),
- the mode 3 implies the hybrid operation of the EM and the HM via ICE,
- the recharge of the electric battery via ICE (mode 4),
- the regenerative braking (mode 5)- the part of the kinetic energy during braking phase is recuperated to charge the electric battery.