Journal of Cleaner Production 189 (2018) 116–127

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Rule-based energy management for dual-source electric buses extracted by wavelet transform☆

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ARTICLE INFO

Article history:
Received 9 December 2017
Received in revised form
16 March 2018
Accepted 5 April 2018
Available online 6 April 2018

Keywords:
Dual-source electric bus
Wavelet transform
Energy management

ABSTRACT

This paper aims at studying the energy management of the dual-source electric bus. Based on the characteristics of the power demand and the energy storage system of the dual-source electric bus, a rule-based control strategy based on wavelet transform is proposed to allocate the energy flow among the energy units to obtain efficient energy transfer. The high and low frequency component power demand are decomposed and reconstructed by wavelet transform theory. The high frequency component power is assigned to the super capacitor, and the low frequency one is assigned to the battery pack or power grid, which can obviously reduce the damage, caused by the power rapid change and surge load, to the battery pack and power grid. The effectiveness of the proposed method is evaluated by the benchmark solved by dynamic programming under both a real driving cycle and the standard China bus driving cycle. Simulation experiments are carried out and the results show that the average power consumption is 0.9335 kWh/km, which has only a difference of 8.25% compared with the benchmark under a real driving cycle. In addition, a 9.02% difference is realized under the standard China bus driving cycle. Finally, the hardware-in-loop experiment is performed and the results show that the proposed strategy is reasonable.

1. Introduction

The development of new energy buses is an important way to solve the problems of environmental pollution and energy shortage (Liu and Kokko, 2013; Zapata and Nieuwenhuis, 2010; Li et al., 2016). With the improvement of energy storage technology, the dual-source electric bus (DSEB) has developed rapidly with its advantages of environmental protection, energy saving, good dynamic performance and maneuverability (Hamacek et al., 2014; Bartlomiejczyk and Mirchevski, 2014; Tica et al., 2011; Sun et al., 2014). DSEB has two energy sources, the power grid and energy power system. The energy power system includes the battery pack and super capacitor (SC). Thus they have two driving modes, one is on-grid mode when the bus is powered by the connected power grid, and the other is off-grid mode when the bus is powered by the energy storage system. Two driving patterns can help DSEB to overcome many deficiencies, such as limitation of driving ranges, restriction on grid network layout, visual pollution due to grid networks at the intersections and so on. The SC mounted on DSEB has high power density that can satisfy the instantaneous high power demand. Meanwhile, DSEB can really achieve zero emissions of pollutants and have better energy-saving ability, emission reduction and economic performance compared with the hybrid electric buses (Trovão et al., 2013; Siemionek and Dziubiński, 2015; Ritter et al., 2016). However, each power source has its own characteristics, namely, batteries and SC have high energy density and high power density, respectively, and the grid is capable of supplying continuous and stable power. How to make full use of the different characteristics of these three power units to improve the economic performance of DSEB is the key issue for the development of DSEB. In order to maximize the role of each power source, a reasonable control strategy must be developed to allocate the power between the power sources.

Many studies have been done on power distribution and energy

☆ The short version of the paper was presented at ICEEE2017/ISEV2017 on July 26–29, Sweden. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.jclepro.2018.04.054
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management of electric vehicles with multiple power sources (Trovão et al., 2013; Mohamed et al., 2014; Bizon, 2012; Wang et al., 2010; Khayyam and Bab-Hadiashar, 2014; Zhang and Xiong, 2015; Chen et al., 2014a, 2014b). Ref (Trovão et al., 2013) presented an integrated rule-based meta-heuristic optimization approach to deal with a multilevel energy management system for a multi-source electric vehicle. The proposed method is able to fulfill the requested performance with better source usage and much lower installed capacities. Ref (Mohamed et al., 2014) developed a fuzzy controller for a grid-connected charging park including plug-in hybrid electric vehicles (PHEVs) which can reduce the overall daily cost of charging the PHEVs, mitigate the impact of the charging park on the main grid, and shave the peak load curve. Ref (Bizon, 2012) analyzed the energy efficiency for the multiport power converters (MPCs) used in plug-in fuel cell vehicles (PFCVs), and proposed a generic MPC architecture as a competitive topology for PFCV from both efficient and flexible energy management point of view. Ref (Wang et al., 2010) proposed an energy management of pure electric vehicles based on a fuzzy logic control, which can split the power between batteries and ultra-capacitor in a more reasonable way to satisfy the demand of better performance. Ref (Khayyam and Bab-Hadiashar, 2014) proposed an adaptive intelligent energy management system, which can adjust the different power sources operations under different driving cycles by online self-learning. Ref (Zhang and Xiong, 2015) proposed an adaptive hierarchical energy management for a PHEV based on driving pattern recognition and DP algorithm, and this proposed method can achieve better fuel efficiency than the conventional DP-based control strategies. Ref (Chen et al., 2014a, 2014b) presented intelligent control methods for a PHEV based on genetic algorithm, neural networks, dynamic programming and quadratic programming, which can control the battery current effectively and reduce the fuel-consumption.

Recently, some works (Zhang et al., 2008; Pan et al., 2015; Ates et al., 2010; Njoya Motapon et al., 2014; Li et al., 2015; Ibrahim et al., 2015) focused on the power distribution based on wavelet transform methods. Ref (Zhang et al., 2008) proposed a wavelet transform based strategy for the power management of hybrid electric vehicles with multiple on-board energy sources combined with fuel cells, batteries and an ultra-capacitor. Different frequency components of the total power demand were allocated to these three power components to achieve an optimal power management. Ref (Pan et al., 2015) presented an approach based on fuzzy control and wavelet transform, which can manage the output of three power sources for a hybrid electric tracked bulldozer. Ref (Ates et al., 2010; Njoya Motapon et al., 2014; Li et al., 2015; Ibrahim et al., 2015) studied the wavelet transform based energy management with several control methods for hybrid power systems including the fuel cell system to allocate the power demand which demonstrated the great flexibility and generality of the wavelet transform based control strategies. Although there are many related literatures, most of them mainly focused on the power demand sharing for fuel cell vehicular power systems.

Considering the DSEB combined with power grid (through power collection system)/battery pack/SC, SC has the advantage in handling transient loads (Husain, 2003) and the batteries and power grid can output stable power as soon as possible. Coincidently, wavelet transform is capable in decomposing unsteady state and transient signal into high and low frequency components (Zhang and Mi, 2011), which is suitable for power control by using wavelet transform theory. Although many literatures focusing on the energy distribution based on wavelet transform for electric vehicles, wavelet transform based control method applying to electric buses combined with the energy supplied by power grid is still insufficient. Therefore, an energy management strategy based on wavelet transform for DSEB is proposed in this paper.

Wavelet transform procedure is used to extract the transient high frequency power demand to SC of DSEB, and the low frequency component of the power demand are distributed to the battery pack or power grid. Reasonable allocation of high and low frequency power demand can reduce the damage of power system, caused by the rapid changes of power and surge load, thus ensuring the batteries durability and power grid stability, delaying the batteries lifespan and making it realization in engineering applications (Xiong et al., 2017a). The proposed strategy is analyzed under a real driving cycle constructed by real driving data and the standard China bus driving cycle. Moreover, the results are compared with the benchmark solved by the global optimal control strategy based on DP to evaluate the effectiveness of the proposed energy management. In addition, the hardware-in-loop (HIL) experiment is also conducted to evaluate the reasonable and feasibility of the proposed strategy. The outline of this paper is shown in Fig. 1.

The remainder of this paper is organized as follows. In Section 2, the modeling of the dynamic system is introduced, which includes the battery pack, SC and traction motor, and the construction of the real driving cycle is designed. The methodology of energy management strategy based on wavelet transform is illustrated in Section 3. Section 4 presents the experimental results and discussion. Finally, the conclusion is summarized in Section 5.

2. Dynamic system modeling and real driving cycle construction

DSEB is powered by electricity grid and energy power system (containing the battery pack and SC). The analysis of the dynamic performance and driving conditions of the vehicle is the prerequisites for optimizing control of energy consumption.

2.1. Basic parameters of DSEB

The basic parameters for DSEB are shown in Table 1.

The power system of DSEB is shown in Fig. 2, which is composed of the power collection system, isolated DC/DC converter, battery pack, SC, bidirectional DC/DC converter, motor inverter and so on. The front end of the power collection system is connected with power grid. The grid provides electrical energy through the power collection system and isolated DCDC converter, together with the output power from the battery pack and SC to drive the vehicle. Generally, the grid and SC supply electricity when the bus drives on-grid, connected with power grid. The power batteries and SC supply energy when the bus drives off-grid, removed from the grid.

2.2. Dynamic system modeling

The energy storage system of DSEB is composed of power grid, battery pack and SC. Power grid is capable of supplying continuous power. Since the grid is deployed and managed by the national Grid, it is not discussed and studied here. The battery pack is consisted of lithium batteries from ATL, and the nominal voltage is 521.7 V. SC is made of 15 monomers in series from MAXWELL. Each monomer's nominal voltage is 48 V and the capacity is 165 F. The isolated DC/DC converter and bidirectional DC/DC converter have not been modeled here, but their energy conversion efficiencies have been taken into account.

2.2.1. Modeling of the battery

Lithium battery has incomparable advantages in various types of power batteries, which has the characteristics of long lifecycles, low calorific value, good thermal stability, and good environmental safety and so on. Battery models commonly used include Rint