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Design and analysis of a fuel cell supercapacitor hybrid construction vehicle

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ABSTRACT

Fuel cell hybrid construction vehicles (FCHCVs) are an attractive long-term option for the propulsion of CVs. This paper presents an approach for the design and analysis of an FCHCV with supercapacitors as the energy-storage device. The design stage includes determination of the topology of the electrical system, energy flow analysis, and a determination of the energy-storage system. Due to the markedly changing loads, supercapacitors with high specific power and high durability seem the best choice. A control strategy based on Pontryagin's minimum principle is proposed considering hydrogen consumption, the state of charge of the supercapacitors, and fuel cell durability in the cost functions. With the selected design and proposed strategy, we propose a power source sizing methodology, and its economic influence is evaluated for both present and future FCHCVs. This study was performed with a system-level model of an FCHCV in MATLAB environment. Simulation results demonstrate the superiority of the proposed strategy. Optimal power source sizes can be chosen by specific criteria of hydrogen consumption and powertrain cost. FCHCVs will become very attractive, assuming that the related costs are reduced in the future.

Introduction

Construction vehicles (CVs) are important construction equipment, and include loaders, bulldozers and scrapers. Compared with passenger cars, CVs have additional operating loads, because they typically move and work at the same time. CVs have disadvantages of low energy efficiency, high fuel consumption, poor emissions, and noise. Energy saving and emission reduction with respect to CVs have always been hotspots in the construction industry. With the increasing energy shortage and environmental pollution, these problems have become of deeper concern. In recent years, hybrid CVs have been introduced and developed, but they could not be separated from conventional engines and they are not ‘green’ power sources. With the successful application of fuel cell (FC) hybrid vehicles (FCHVs), there is enough interest to look at their application to CVs. The first application of an FC hybrid CV (FCHCV) is an underground loader. In 2000, Wagner and INCO Company carried out tests on an FC-powered electric

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underground loader [1–3]. The Fuelcell Propulsion Institute and Vehicle Projects LLC jointly promoted a project for FC-powered mining vehicle. In 2004, Caterpillar participated in the project and introduced an FC underground loader based on the R1300 underground loader, with a proton exchange membrane FC (PEMFC) and a nickel metal hydride battery [4]. The current research mainly focuses on the field of FC underground loaders [5,6]. Because there are no waste gas emissions, FC underground loader reduced the entire mining cost, as compared with the battery electric loaders; thus it has a great advantage [7–9]. FC mining equipment is well suited to applications in the mining industry, which is one of the future directions of industrialization.

Due to the complex working environment, the operating load on CVs can change markedly and frequently. To drive the hydraulic system in CVs, the maximum required power could account for 40–60% of the rated power of the engine [10]. A standalone FC system cannot meet the demands of the frequently changing load, especially during cold-start, peak power demand or transient events, for CVs application. In addition, the FC system cannot store the regenerative energy. Therefore, to employ FC in CVs, there must be at least an auxiliary power source to improve vehicle performance. Hybridization with high specific energy storage devices such as battery and supercapacitor (SC) has important advantages in FC system [11,12]. Hybridization can help operate FC system in better operating conditions, leading to an increase of FC system performance. The energy-storage system (ESS) is usually a battery module, a SC module, or a combination of both. A lot of work has been conducted to investigate the comparison, optimal sizing and control strategies for FC-batteries, FC-SC, and FC-batteries-SCs hybrid vehicles [11–13]. These studies have referenced significance for the design and analysis of FCHCVs. CVs are usually equipped with a fluid torque converter, and the powertrain efficiency is poor. By hybridization, FCHCVs can improve powertrain efficiency and recover the braking energy, the energy saving effect will be much attractive. In addition, FCHCVs can also address the problems of vibration and noise from diesel engines.

Though a lot of efforts have been made in order to introduce FCHVs to commercial applications, however, the main limitation is the cost and durability of the FC stack (FCS) system, which is generally regarded as the main challenge to the commercialization of various FCHVs [14–17]. Technologies and policies related to the cost problem could to be further improved. With regard to the durability of the FCS, the United Technologies Corporation and other companies have continuously introduced high durability FCS products [18]. For automotive applications, the FCS usually works under complex operating conditions, including start/stop and frequently changing load condition. This is the main reason why the durability of automotive FCS is shorter than that of the stationary ones. For FCHCVs, the performance of the FCS can be improved by properly distributing the power demand between the FCS and ESS. The power distribution is linked to energy management strategy (EMS) of the hybrid system. Currently, the EMS of FCHVs can be divided into two major groups: one is based on the heuristic concept, the other is based on the optimal control theory. The former mainly indicates strategies based on control rules, such as rule-based algorithms and fuzzy logic algorithms [19,20]. These strategies are relatively simple and they could not guarantee the optimal hydrogen economy. The optimal control theory has been introduced to EMS, such as strategies based on dynamic programming (DP) and Pontryagin's minimum principle (PMP) [15,21,22]. Although DP approach can guarantee global optimality, the driving cycle must be known in advance, so it is difficult to be used for online control. PMP-based strategies can optimize the power distribution online, and they can take into consideration the FC durability and hydrogen economy at the same time. Another important challenge to FCHCVs is to choose the optimal powertrain topology and power source size, in combination with an optimal EMS. Thus, an FCHCV with high hydrogen economy, reliability, performance, and low cost can be designed.

To this end, the design and analysis of an FC-based hybrid system oriented to CVs applications are studied in this paper. We hope to address the problems of cost and durability of the FCS through optimal control strategies and optimal power source sizes, with attractive performance. FCHCVs research is particularly significant, and it has good applications in construction machinery. This paper is organized as follows: In Section System structure, the topology of the electrical system for an FCHCV is discussed, including energy flows analysis of the hybrid system, and a determination of ESS. The system model of the FCHCV is established in Section System model. In Section EMS based on PMP, a PMP-based control strategy is proposed, considering hydrogen consumption, state of charge (SoC) of SC, and FC durability in cost functions. In Section Results and discussion, comparison simulations of the proposed strategy, basic PMP strategy and DP strategy are performed. Based on the selected design and the proposed strategy, a power source sizing methodology is proposed, and economic influence for power source sizing is evaluated for both present and future FCHCV. Finally, the conclusions are summarized in Section Conclusion.

System structure

The electrical structure for an FCHCV essentially involves an FCS with auxiliary systems, an ESS, and driving components which are generally electrical motors. The FCS is an electrical power source, because its DC output voltage drops with the increase of the working current according to its polarization characteristic, it needs to incorporate a power converter to regulate the voltage change. The ESS can store energy produced by the FCS and deliver the energy to loads. In addition, the ESS can store energy recovered from braking though electric motor/generator. Therefore, the power converter of the ESS must be a bidirectional converter, which allows energy flows in both directions. In this section, we address the design of the electrical structure for an FCHCV, focusing on the determination of the electrical topology and the selection of the ESS, and the energy flows in FCHCV are analyzed. This paper takes a typical 5-ton wheel loader as a prototype to study the FCHCV. Loader is a typical CV, the research of the FC hybrid loader can also apply to other CVs.