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Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship

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ABSTRACT

Hybrid fuel cell propulsion systems for marine applications are attracting widespread interest due to the need to reduce ship emissions. In order to increase the potential of these systems, the design of an efficient energy management strategy (EMS) is essential to distribute the required power properly between different components of the hybrid system. For a hybrid fuel cell/battery passenger ship, a multi-scheme energy managements strategy is proposed. This strategy is developed using four schemes which are: state-based EMS, equivalent fuel consumption minimization strategy (ECMS), charge-depleting charge-sustaining (CDCS) EMS, the classical proportional-integral (PI) controller based EMS, in addition to a code that chooses the suitable scheme according to the simulation inputs. The main objective of the proposed multi-scheme EMS is to minimize the total consumed energy of the hybrid system in order to increase the energy efficiency of the ship.

The world's first fuel cell passenger ship *FCS Alsterwasser* is considered and its hybrid propulsion system is modelled in MATLAB/Simulink environment. The performance of the developed multi-scheme EMS is compared to the four studied strategies in terms of total consumed energy, hydrogen consumption, total cost and the stresses seen by the hybrid fuel cell/battery system components considering a daily ship operation of 8 h. Results indicate that a maximum energy and hydrogen consumption savings of 8% and 16.7% respectively can be achieved using the proposed multi-scheme strategy.

Introduction

The minimization of the negative environmental impacts of shipping and improving ships energy efficiency have generated considerable recent research interest. This concern is enhanced by the introduction of more stringent environmental regulations by the International Maritime Organization (IMO) to control ship emissions. Hybrid electric power and propulsion

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concepts have been suggested as an energy efficiency design index (EEDI) reduction measure adopted by the IMO to help ships to comply with the new international regulations [1,2]. In order to make hybrid propulsion systems greener, fuel cells can be used in these systems as a main source of power [3].

Proton exchange membrane fuel cell (PEMFC) has the advantages of zero emissions, quick start-up, high efficiency, high power density, low operating temperature, solid electrolyte, and low noise which promote the application of PEMFC in the transportation sector [4,5]. A battery system is usually used as an energy storage technology to hybridize the fuel cell propulsion system in transportation applications in order to improve the efficiency of the fuel cell system and its dynamics [6]. The presence of the fuel cell and battery systems together requires an energy management strategy (EMS) to improve the electrical integration of the system.

Development of a suitable EMS is a basic issue for hybrid fuel cell propulsion systems to properly split the required power between the fuel cell and battery systems. EMS controls the dynamic behaviour of the hybrid system, its fuel consumption, and affects the system efficiency, weight, size, and lifetime of its components [7,8]. Therefore, efforts have been made to investigate different EMS. These strategies may aim to minimize hydrogen consumption [9], maximize fuel cell efficiency or overall efficiency [10], reduce stresses on the hybrid system components [11], maintain battery state of charge (SOC) or the bus voltage at a certain level [9,12,13], minimize the operational cost [14] or minimize the hybrid system weight and size [8]. Whilst most of the studies about EMS give their attention to the hydrogen consumption, which is certainly important, in this paper more focus is concentrated on the total consumed energy taking into consideration the battery depleted energy and the required energy to recharge the battery back to its initial SOC for the purpose of improving the energy efficiency of the examined ship. By taking the battery discharge energy during the voyage and the required energy to recharge it back to its initial SOC into account, the total consumed energy can be accurately obtained and different energy management strategies are fairly compared.

The literature review in the area of power distribution of hybrid fuel cell propulsion systems is dominated by automotive industry applications; however, there have been a few studies that investigated this problem for marine applications. In hybrid fuel cell propulsion systems, the fuel cell system can be used to supply the average required power in a load-levelling mode as suggested for small ships and underwater vehicles in Refs. [15,16]. An alternative approach was proposed in Ref. [3] for a Korean tourist boat to use the fuel cell system in a load-following mode to provide the required power. Meanwhile, the battery system is used as a supplement to the fuel cell system and charged or discharged when the required load power is lower or higher than the available fuel cell power. For the hybrid fuel cell/battery passenger ship *FCS Alsterwasser*, a state-based EMS was developed in order to maximize the hybrid system efficiency [10]. Also, an improvement to the classical PI controller based EMS was presented in Ref. [17] for the *FCS Alsterwasser* that takes into account the fuel cell efficiency as an input to the EMS which results in reducing the fuel cell operational stress and its hydrogen consumption. A fuel cell/battery/ultra-capacitor hybrid power system was proposed for the same ship with a fuzzy logic EMS with an objective of enhancing the hybrid system performance [18].

Due to the fact that each EMS has its main objective, there remains a need for using a multi-scheme EMS to improve the performance of hybrid fuel cell systems [11]. This study represents a new approach to design an efficient multi-scheme EMS for hybrid fuel cell/battery propulsion systems of ships that have significant variation in its power demand. The approach used in this study aims to compare different energy management strategies at different battery SOC and different load levels for a hybrid fuel cell/battery passenger ship. This comparison is then used to develop a multi-scheme EMS for the first time that switches between different strategies during the voyage of the examined ship based on the battery SOC and the required load power in order to reduce the energy consumption of the hybrid fuel cell system and improve its energy efficiency. Four different EMS are implemented for the comparison which are: state-based EMS, equivalent fuel consumption minimization strategy (ECMS), charge-depleting charge-sustaining (CDCS) EMS, and the classical proportional-integral (PI) controller based EMS. These strategies are the most common and they are chosen for their simplicity and ease of realizability while other strategies are more complex and require longer computational time [11]. The four strategies are combined to develop a multi-scheme EMS with an objective of minimizing the total consumed energy. Considering a daily operation of the ship of 8 h, the five EMS are compared in terms of the consumed energy, hydrogen consumption, operational cost, and the stresses seen by the fuel cell and battery systems. Sensitivity analysis of different initial battery SOC as well as different energy prices are made to assess its effects on the results of the developed multi-scheme EMS.

The ship hybrid fuel cell propulsion system as well as different energy management strategies are modelled in MATLAB/Simulink environment which is a flexible environment using the Simscape Power Systems (SPS) toolbox [19]. The paper is organized as follows. Section Description of the ship & voyage introduces the examined ship and voyage. Section Energy management strategies describes different EMS while Section Simulation implementation illustrates the simulation implementation of the hybrid fuel cell propulsion system and different EMS. Section Results & discussion shows the simulation results and discussion. Finally, Section Conclusions presents the work conclusions.

Description of the ship & voyage

The world's first hydrogen fuel cell passenger ship *FCS Alsterwasser* was developed in Germany as a part of the *Zemship* (Zero Emission Ship) project [3,20]. The total project budget was €5.5 million, of which €2.4 million was co-funded by the European Union life program [21]. A hydrogen fuelling station has been also built for this ship as a part of the project. This ship is used as a case study in this paper and its main specifications are shown in Table 1.

This ship is equipped with two PEMFC systems and a DC–DC converter to stabilise the fuel cell voltage. The fuel cell system is hybridized with a lead-gel battery system to deliver the