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Determination of the component sizing for the PEM fuel cell-battery hybrid energy system for locomotive application using particle swarm optimization

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A B S T R A C T

This paper presents an optimization approach for optimal component sizing of PEM fuel cell (PEMFC)-battery hybrid energy system (HES) to provide the driving force required to haul passenger trains. The objective function is the minimization of the cost of HES, which subjects to the constraints of battery state-of-charge limit, PEMFC capacity constraint, and the instantaneous power balance constraint. A model of PEMFC-battery HES suitable for locomotive application is formulated. Two energy management strategies (EMS) are proposed to ensure the balance between instantaneous power demand and supply. The EMS is suitably incorporated into the particle swarm optimization based solution algorithm. Three practical drive cycles are used in the simulation study. The simulation study reveals that the sizes of PEMFC and battery depend on the choice of EMS, average speed of train, and slope of the railway track. The fuel consumption and dynamic behaviour also depend on the choice of EMS.

1. Introduction

The development of economically feasible renewable energy systems to replace fossil fuels is one of the most significant areas of research in this century to the research communities around the globe. Most of the energy demand of the present world is met with the conventional fossil fuels. However, the fossil fuel reserve on earth is finite. Thus, it may be only a matter of time when these reserves would run out. Also, burning of fossil fuels releases greenhouse gases which cause environmental pollution and global warming. All these motivate the researchers to find some alternative sources of energy. Hydrogen is one such green energy source. In the recent years, the pace of investment in developing technologies for hydrogen fuelled energy sources, is greatly increased. Fuel cell (FC) is one such technology. There are various types of fuel cell which can be used in different applications [1]. Proton exchange membrane fuel cell (PEMFC) is a type of FC having several advantages, such as, higher power density, lower operating temperature, high efficiency etc. Due to the relatively lower operating temperature, this form of FC can be used in replacing the traditional petroleum-based drives [2]. However, the notable drawbacks in deploying PEMFC are high cost, shorter lifetime, slow dynamic response etc. In [2–4], it is shown that the hybridization of PEMFC with some energy storage systems (ESS) is essential to alleviate some of these technical drawbacks. The hybridization of PEMFC with ESS also improves the dynamic response of the system, reduces the fuel consumption etc. Different types of batteries and/or ultra-capacitor are used as ESS.

In the recent years, a lot of research articles is reported in developing the PEMFC-battery-based hybrid energy system (HES) for transportation applications. There are two different research directions. In some of the works, different types of control approaches are reported for developing the energy management strategy (EMS) to control the power flow in the HES, such as, fuzzy-logic-based control, optimal adaptive control etc. Some works are focused on the development of the optimization approach. These approaches can be of two types: (i) design optimization (DO) approach for the optimal component sizing of the HES and (ii) energy management optimization (EMO) approach for developing an optimal EMS. The approaches combining both DO and EMO are also reported in some of the articles. In these approaches, different types of objective function are formulated which are optimized under certain constraints, such as, the vehicle performance constraints in terms of acceleration time, gradeability, the constraints on the dynamic performances of the power sources and ESS etc. To solve these optimization approaches, several solution strategies are used. These can be categorized into: (i) mathematical and enumerative approaches, such as, non-linear programming, dynamic programming etc., and (ii) meta-heuristic approaches, for example, genetic algorithm, particle swarm optimization (PSO) etc. A comprehensive review on each approach [2–30] is given in Table 1.

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Table 1
comprehensive information on the research on PEMFC-battery hybrid energy system used in transportation applications.

Ref.	Approach	Objective	Solution Strategy	Application	Remarks
2	DO	Determination of the optimal degree of hybridization (DOH)	Heuristic	Hybrid vehicle	Use of different types of storage system depending on power/energy ratio.
3	DO	Maximization of energy efficiency and minimization of storage mass/volume	Heuristic search	HEV	Comparison between two topologies of PEMFC and super-capacitor bank to the drive-train DC link is done.
4	DO	Minimization of hydrogen consumption and vehicle mass	Heuristic search	Hybrid vehicle	Charge sustaining EMS proposed. No optimization of EMS performed.
5	Control approach	To improve the operational efficiency	Adaptive control	Tramway	EMS consists of eight modes of operation. Power demand, vehicle speed, and battery state-of-charge (SOC) determines the mode of operation to be followed.
6	Control approach	Maximization of efficiency of hybrid energy system and reduction in the size of FC	Control strategy with FC as range extender	Wheelchair	EMS determines the power split among the energy sources considering the slow dynamics of the FC.
7	Control approach	Maximization of efficiency of hybrid energy system.	Fuzzy logic control	Hybrid vehicle	Power output of the energy sources is determined by applying fuzzy theory on the battery SOC, power demand and power output of FC
8	Control approach	Maximization of efficiency of hybrid energy system.	Fuzzy logic control	Hybrid vehicle	Power output of the energy sources is determined by applying fuzzy theory on the battery and UC SOC, power demand and power output of FC and ultra-capacitor (UC)
9	DO	Minimization of investment and operating cost	Rule based deterministic algorithm	PHEV	Optimization variables are battery capacity, stored hydrogen mass, FC power rating. No meta-heuristic search technique used.
10	DO	Minimization of the cost and mass of the overall system	Deterministic algorithm with gradient technique	HEV	Design variables are number of units of FC and ESS.
11	DO	Minimization of the mass, cost and volume of the hybrid energy system	(GA), (PSO)	HEV	Design variables are number of units of FC and ESS.
12	DO	Minimization of hydrogen consumption and vehicle cost	Multi objective GA	PHEV	GA algorithm is written in MATLAB and evaluation of objective function and constraints is done in ADVISOR.
13	DO	Maximization of the efficiency and Minimization of the mass and cost of the overall system	Non-linear programming	HEV	New topology of FC-battery-UC is proposed. Design variables are number of units of battery and UC.
14	DO	Minimization of the mass of the hybrid energy storage system	Branch and bound algorithm	HEV	Design variables are number of units of battery and UC. Constraints are the maximum values of specific energy and power related to Ragone plots.
15	DO + EMO	Minimization of the component purchase cost, fuel cost, maintenance cost and cost of energy required for battery charging.	Branch and bound algorithm	Plug-in hybrid electric mini-excavator	Battery ageing constraint is additionally considered
16	DO + EMO	Minimization of the component purchase cost, fuel cost and maintenance cost.	Branch and bound algorithm	Plug-in hybrid electric mini-excavator	FC and ESS ageing constraints are additionally imposed.
17	DO + EMO	Minimization of the fuel consumption and battery energy usage	Stochastic dynamic programming (DP)	HEV	Compressor diameter, degree of hybridization, battery SOC, FC current density are the optimization variables.
18	DO + EMO	Maximization of the fuel economy and minimization of the system cost	Multi-objective GA	Transit bus	GA algorithm is written in MATLAB and evaluation of objective function and constraints is done in ADVISOR.
19	DO + EMO	Minimization of hydrogen consumption	GA for DO and DP for EMO	HEV	Total mass is sum of FC mass (function of its rated power), battery mass (function of its capacity) and vehicle mass. The optimization leads to the reduced size of FC and battery.
20	DO + EMO	Minimization of the vehicle cost and fuel consumption	Multi objective PSO	PHEV	Motor power rating is additionally considered as the design variable.
21	EMO	Minimization of fuel consumption	GA	HEV	Optimal power split between the energy sources is determined.
22	EMO	Offline EMO aims at minimization of fuel consumption. Real time EMO aims at minimization of fuel consumption and battery power contribution.	DP, Pontryagin's minimum principle for offline EMO and GA for real time EMO	Transit Bus	Real time optimization results in less fuel consumption as compared to the offline optimization.
23	EMO	Minimization of fuel consumption and maximization of efficiency of the hybrid power system	Real time optimization using MATLAB toolbox	Hybrid vehicle	Optimal power split between the energy sources is determined. Optimization toolbox used is not specified.
24	EMO	Minimization of fuel consumption and fuel cell degradation	Rule-based deterministic algorithm	Hybrid vehicle	Battery degradation is not considered.
25	DO	Minimization of cost	Exhaustive search on feasible objective space	HEV	Design variables are number of units of FC and UC.
26	EMO	Minimization of hydrogen consumption	Global optimisation algorithm based on optimal control theory	HEV	Optimal power split between the FC and ESS is determined.
27	EMO	Minimization of hydrogen consumption and difference between initial and final battery SOC	Multi-objective GA (MOGA)	HEV	Optimization variables are number of FC units and their efficiency, battery maximum SOC and super-capacitor minimum SOC.
28	DO	Minimization of cost of the hybrid energy system	Heuristic search	Locomotive	No optimization technique is used.
29	DO	Determination of component sizing of the hybrid energy system	Bisection method	Locomotive	Fuzzy logic-based EMS is proposed. No optimization of EMS is performed.
30	DO + EMO	Minimization of hydrogen consumption	Exhaustive search for DO, EMS based on classical optimal control theory.	HEV	Hydrogen economy maps for different combination of FC and ESS sizes are provided.