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An innovative optimal power allocation strategy for fuel cell, battery and supercapacitor hybrid electric vehicle

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ABSTRACT

An optimal design of a three-component hybrid fuel cell electric vehicle comprised of fuel cells, battery, and supercapacitors is presented. First, the benefits of using this hybrid combination are analyzed, and then the article describes an active power-flow control strategy from each energy source based on optimal control theory to meet the demand of different vehicle loads while optimizing total energy cost, battery life and other possible objectives at the same time. A cost function that minimizes the square error between the desired variable settings and the current sensed values is developed. A gain sequence developed compels the choice of power drawn from all devices to follow an optimal path, which makes trade-offs among different targets and minimizes the total energy spent. A new method is introduced to make the global optimization into a real-time based control. A model is also presented to simulate the individual energy storage systems and compare this invention to existing control strategies, the simulation results show that the total energy spent is well saved over the long driving cycles, also the fuel cell and batteries are kept operating in a healthy way.

1. Introduction

Due to the concerns about the depletion of gasoline and its adverse environmental impact, there has been a dramatic shift in strategy to utilize pollution free renewable energy sources in vehicles. Fuel cell electric vehicles (FCEV) hold tremendous promise in this regard to replace fossil fuel in the long run. Although the fuel cell itself can be considered as a power source with nearly unlimited energy (only limit to hydrogen tank size) and almost zero pollution, there are obstacles such as high cost per unit power, poor transient performance, and inability to allow bi-directional power flow that need to be overcome. While progress is being made in fuel cell technology, there is an immediate need for efficient design of hybridization of the vehicle power train. Benefits from such design include capturing regenerative braking energy, lowering cost per unit power, providing optimization possibility and mitigating the stress on the fuel cell stack by shifting some portion of dynamic power demand to a second power source thus improving fuel cell life and efficiency.

This article introduces an optimal design of an innovative hybrid power system in a FCEV. Based on physical limits of cost, mass, and volume as well as load change limits, a hybrid system that includes fuel cells, battery, and supercapacitor as energy sources is designed. The design is implemented to take full advantage of each source's capabilities. In doing so, an active power-flow control strategy from each energy source based on optimal control theory is proposed here. The innovative power allocation strategy allows optimized power flow between fuel cell and battery. A cost function is established that minimizes the squared error between the desired variable settings and current settings. The optimization uses the current battery state of charge (SOC), battery SOC at the end of the cycle, and average power flow as optimization parameters in the cost equation. Weights are placed on these values to optimize for specific goals such as controlling the battery SOC ripple or reduced variation in fuel cell power flow. By updating the coefficients on real time basis, fuel used is limited while maintaining both components in their better, if not best working range. By implementing this technique, a set of feedforward and feedback algorithms is designed, and updating method of the controller is also evaluated.

Considering all nonlinearities of the whole power system, the robust controller as well as another instantaneous controller for battery/supercapacitor hybrid is programmed. The additional controller uses a smaller size supercapacitor to assist the battery and make the battery stack work in an even better way. The paper has simulated the whole vehicle energy flow based on different driving

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cycles using Matlab-Simulink and its energy efficiency is compared to other existing control strategy for FCEV.

2. Background, theory and calculation

2.1. Fuel cell, battery, and supercapacitor hybrid system design

Almost all existing hybrid power systems of FCEV mainly composed of fuel cell/battery hybrid (F/B) [1–4] or fuel cell/supercapacitor hybrid (F/C) [5–10]. For example, Toyota has made a FCEV based on F/B hybrid using a nickel–metal hydride (NIMH) battery pack as a second energy source, and Honda has made another model based on F/C hybrid using supercapacitor cells as power buffers. It is expected that fuel cell/battery/supercapacitor (F/B/C) hybrid can result in superb system performance and energy efficiency. Research is only starting to look at the use of all of these components in a hybrid vehicle [11].

For an F/B hybrid, the fuel cell stack supplies the cruising power, while the battery has three main functions: driving the fuel cell auxiliaries, providing additional power required for acceleration, and receiving regenerative braking energy. The battery used here can be lead acid, NIMH batteries or lithium-ion batteries.

A DC–DC boost converter is required at the fuel cell side and another bi-directional DC–DC converter is necessary at the battery side [12,13]. A boost converter is typically used to boost-up the fuel cell voltage to a DC bus (typically 300–500 V for commercial motor drives), while a bi-directional DC–DC converter can be configured as an isolated buck, boost or buck-boost type, depending on the battery stack configuration [14–17]. If an AC motor is used, then a DC/AC inverter is needed at the DC bus side.

Some published works indicate that the fuel cell or the battery can be connected directly to the high voltage bus while the other energy storage device's output current is actively controlled via the DC converter [2,3], thus one of the two DC converters can be neglected, that help to reduce some design complicacy. However, Thounthong et al. [4] suggested that fast load demand will cause a high voltage drop at the fuel cell side, known as the fuel starvation phenomena. On the other hand, battery voltage is always known to vary depending on the specific load and can be deeply drained. Therefore, neither fuel cell nor the battery could be an ideal constant voltage source for providing required power alone. Furthermore, the motor drive efficiency and the exact load current limit are hard to estimate due to the varying DC voltage value; therefore, for analyzing the control strategy, it is assumed the inverter has a constant DC voltage at input. The addition of DC–DC converters is thus necessary for implementing this active power flow control strategy.

For F/C configuration, fuel cell serves as the main power source, while the supercapacitor bank replaces battery in F/B configuration. While a supercapacitor has high power density it does not have very high energy density and cannot act as a good energy buffer. Therefore, if the required peak power in a vehicle load is much larger than the fuel cell peak power for an extended time, a very large stack of supercapacitors would be required. This would add considerably to the cost.

Considering the advantages and disadvantages of the different power sources in the above discussion, a new power system with an innovative power allocation strategy is proposed that integrates all three components (fuel cell, battery and supercapacitor) together. A schematic of three power component system is shown in Fig. 1. All three converters are required here but are integrated into one global converter with individual controls. All three power system components are actively controlled.

A supercapacitor could have a SOC that varies widely without affecting its life and, therefore, can be considered a power buffer. For this reason in the initial power flow optimization among the three energy storage devices the energy stored in the supercapacitor was neglected. Thus, the power system was divided into two parts, F/B hybrid and battery/supercapacitor (B/C) hybrid. In later part of the paper the F/B hybrid is proven to be able to minimize the energy cost while keeping battery working in a best SOC operating range. The B/C hybrid can provide a best power combination for any transient power request.

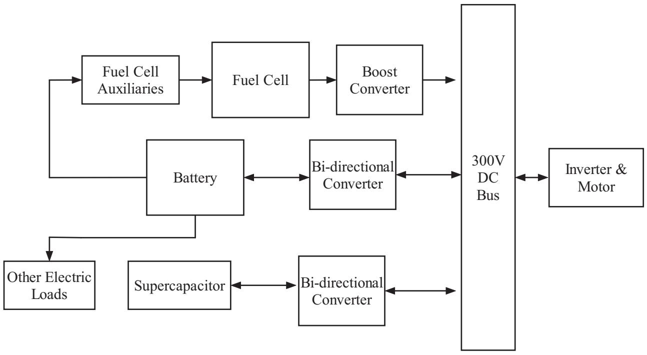

Fig. 1. Fuel cell, battery and supercapacitor hybrid vehicle power system configuration.

In this case, the new control system has integrated all merits of the F/B and F/C systems. Thus, the vehicle is possible to be optimized to obtain the longest lasting mileage and largest instant power with limits on cost, mass and volume.

2.2. Sizing of vehicle energy storage system

The vehicle platform for the FCEV used to exemplify this control system has characteristics in Table 1. The energy storage system is designed following a static optimization rule [18,19].

Considering the vehicle model in Table 1, for meeting energy and power requirements, we need to enforce the following equations:

$$W_T = \sigma_B M_B + \sigma_H M_H \geq 90\,\text{kWh} \tag{1}$$

$$P_T = \rho_B M_B + \rho_C M_C + \rho_{fc} M_{fc} \geq 80\,\text{kW} \tag{2}$$

$$P_C = \rho_B M_B + \rho_{fc} M_{fc} \geq 40\,\text{kW}. \tag{3}$$

We also need to minimize

$$V_T = V_B M_B + V_C M_C + V_{fc} M_{fc} + V_H M_H \tag{4}$$

$$C_T = C_B M_B + C_C M_C + C_{fc} M_{fc} + C_H M_H \tag{5}$$

$$M_T = M_B + M_C + M_{fc} + M_H, \tag{6}$$

where W_T is the total vehicle available energy; P_T is the peak total power; P_C is the cruising power; V_T is the total volume; C_T is the total cost; M_T is the total mass; σ_B and σ_H are the specific energy/kilogram for battery and hydrogen tank; ρ_B, ρ_C, and ρ_{fc} are the specific power/kilogram for battery, supercapacitor and fuel cell; V_B, V_C, V_{fc}, and V_H are the specific volume/kilogram for battery, supercapacitor, fuel cell and hydrogen tank; C_B, C_C, C_{fc}, and C_H are the specific cost/kilogram for battery, supercapacitor, fuel cell and hydrogen tank.

There are two directions available. One is try to specify the power and energy targets and minimize the cost, volume and weight. The other direction is to set an approximate maximum target for cost, volume, and weight, and try to maximize the power and energy. A mathematical programming method of such optimization has been introduced in Ref. [18,19]. The