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Combination of Markov chain and optimal control solved by Pontryagin's Minimum Principle for a fuel cell/supercapacitor vehicle

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ABSTRACT

In this article, a real time optimal control strategy based on Pontryagin's Minimum Principle (PMP) combined with the Markov chain approach is used for a fuel cell/supercapacitor electrical vehicle. In real time, at high power and at high speed, two phenomena are observed. The first is obtained at higher required power, and the second is observed at sudden power demand. To avoid these situations, the Markov chain model is proposed to predict the future power demand during a driving cycle. The optimal control problem is formulated as an equivalent consumption minimization strategy (ECMS), that has to be solved by using the Pontryagin's Minimum Principle. A Markov chain model is added as a separate block for a prediction of required power. This approach and the whole system are modeled and implemented using the MATLAB/Simulink. The model without Markov chain block and the model is with it are compared. The results presented demonstrate the importance of a Markov chain block added to a model.

1. Introduction

The need to minimize noxious CO_2 and greenhouse gas emissions has led to an increase in the use of hybrid vehicles in recent years. These vehicles include thermal hybrid vehicles, electrical vehicles equipped with a battery, and fuel cell hybrid vehicles. This article deals with a fuel cell and supercapacitor vehicle. The fuel cell is considered as main power source. It is an electrochemical device that obtains electrical energy by a chemical reaction. The electrical energy is produced without emitting any gas. The Fuel cells have significant advantages, including no emissions, low operating temperature, quick start up, high efficiency and high performance [1]. However, they have some disadvantages that limit their use alone. In fact, the fuel cells response is slow, and cannot able to follow a fast required demand and transient peak power [1]. In the hybrid vehicle, at acceleration and at sudden required power, using the fuel cell as a unique source of power is not sufficient to provide the required power demand during a driving cycle [2]. Also, some problems related at fuel starvation which affect fuel cell reliability and lifetime [3]. The regenerative braking current cannot be returned to fuel cell because it is a unidirectional source [2]. Therefore, due to these reasons, the fuel cell cannot be used as a unique source of power, thus a secondary source of power is needed. A supercapacitor is thus proposed for its very fast dynamic response at sudden required power due to sudden or extreme driving cycle or driving conditions. Whereas, the fuel cell is limited by its slow dynamic response. Also, supercapacitor can recover energy generated from regenerative braking which decrease the hydrogen consumption of the main source. Wherefore, the supercapacitor has the capacity to complement the slower power output of the fuel cell during a driving cycle. Add to this, the supercapacitor charging time is advantageous because it can reach 1 to 10 s, compared with the new fast lithium-ion battery which can be charged at 70% in few minutes [4].

Progress has been made in fuel cell modeling and characterization, and also in understanding the static converters that interact with the fuel cell and components. Nevertheless, manage and optimize of the power in the hybrid fuel cell based vehicle need more investigations. Regardless of the road conditions, the available power must be distributed among the various components to minimize hydrogen consumption and increase the lifetime of the supercapacitor.

Several energy management strategies have been suggested to manage the distribution of power between the two sources and the load, and then to reduce the hydrogen consumption. In reality, the driving condition and driving cycle are unknown. So, the future required power and the sources conditions are unknown. Some power management strategies are based on rules and on the vehicle's current state. For example, a rule based strategy is proposed

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for a plugin hybrid electric vehicle [5]. Another approach of rule based is based on ECMS strategy [6]. Also, a controller based on fuzzy logic is proposed for a fuel cell vehicle [7].

Some optimization strategies require a knowledge of the future conditions and a driving cycle to compute the optimal fuel consumption and the optimal fuel cell power in off-line such dynamic programming (DP) [8], or using optimal control formulation solved by dynamic programming [9] and a real-time optimal energy management strategy based on the determined dynamic programming (DDP) strategy [10]. A multi-dimentional dynamic programming is proposed for an optimal solution to the energy management problem but driving cycle is a priori known [11]. The optimal control problem based on Pontryagin's Minimum Principle is used in real time [12]. Although, knowing some future conditions is required. These conditions can be the cruise time and the available negative energy during braking approached by reference [13]. A PI controller based on Pontryagin's Minimum Principle with three parameters and a fuzzy controller with ten parameters are tested for a fuel cell/battery vehicle implemented in real time with experimental validation [14]. A genetic algorithm and quadratic programming method has been built to improve the fuel economy of a hybrid electrical vehicle and the knowledge of trip information is important to apply this strategy [15].

Some other optimization approaches based on prediction are proposed in literatures. For example, a controller based stochastic dynamic programming (SDP) that can be implemented in real time, the Markov chains was builded on the basis of real-world driving data [16], the stochastic dynamic programming is developed for optimal power management, the Markov memory variable is used to represent the stochastic distribution of driver power demand [17]. In reference [18], a self-optimization energy management using stochastic influences for an electric vehicle is proposed. Also, a Pareto-optimal fronts were proposed for an electrical vehicle by reference [19], to obtain an optimal speeds by solving a multi-objective optimization problem that maximize electric motor efficiency and minimized power consumption. In addition, a model predictive control scheme is proposed to predict the future driving conditions [20]. In reference [21], a rule-based energy management strategy and a model predictive control (MPC) strategy for supercapacitor assisted powertrains is proposed and evaluated. Others predictive methods like a commuter route optimized energy management system is proposed for an hybrid electrical vehicle by reference [22]. A real time optimal control based on dynamic programming and equivalent consumption minimization strategy (ECMS) strategy with long-horizon trip preview information for plugin hybrid vehicles can be found in reference [23]. The preview information is decomposed into future road terrain stored as in vehicle 3D maps and future velocity estimated from streaming or historic traffic data.

In reference [24], a simulation study of a optimal control controller for fuel cell/supercapacitor vehicle for two driving cycle and driving conditions is presented. The driving cycle has been an urbain driving cycle and has been tested at low (Max. 56 km/h) and high (Max. 113 km/h) vehicle speed. The driving conditions was two vehicle masses $m_v = 1625$ kg and $m_v = 2500$ kg. It is shown that the power requirement for the unknown driving cycles and the power distribution among various power source are satisfied. Also the results indicate that the hydrogen consumption is lower during a driving cycle, and the supercapacitor state of charge is bounded at the interval desired. However, at very high vehicle speed (Max. 141 km/h) for driving cycle, the required power is higher. The urbain UDDS driving cycle is selected in this paper, to analyze the performance of the proposed power management strategy. As this cycle has more accelerations and decelerations than other driving cycles, the hybrid vehicle loses more energy and the efficiency of the system decreases. The two problems are shown in this case. In this paper, these problems are observed when the required power can be up to the maximum power fuel cell, and at sudden required power. In the majority of literature, the prediction of the future driving cycle or the future required power have been made for an optimal power management. In this paper, the prediction algorithm has been made to study the effect of speed variation or required power nature on the fuel cell and the supercapacitor.

By using the first strategy in real time, some problems arise when the vehicle reaches a power demand threshold. In this case, the supercapacitor assists the fuel cell even if its state of charge is under the authorised value. This is caused by the fuel cell dynamic which is slow compared with the supercapacitor one. To address this problem, a Markov chain model is proposed to predict the future power demand during an unknown driving cycle.

In this paper, we present a new approach that can be used in real time for a hybrid vehicle supplied by two power sources. The fuel cell is the primary power source and the secondary is the supercapacitor. This approach combines the optimal control solved by Pontryagin's Minimum Principle, and Markov chain to predict future conditions. The power management strategy is developed as a controller based on an optimal control. This proposed method is simple to implement and not required any knowledge of driving cycle or driving conditions or other information related to a derive cycle.

This paper is structured in five sections. In Section 2, the optimal control approach is formulated. In Section 3, Markov chain model is presented. In Section 4, the simulation model is exposed. In Section 5, the simulation results are presented and analyzed. The conclusion is presented in the last section.

2. Formulation of optimal control approach

The proposed approach has to manage the required power and power sources depending on the unknown driving cycle. The objective function is formulated as equivalent hydrogen consumption of the primary and secondary source. Two equations are proposed, thus formulated this objective function. The first equation ($\dot{m}_f(P_{fc}(t))$) is the hydrogen consumption rate from fuel cell, and it depends on fuel cell power. The hydrogen consumption is given in Eq. (1).

$$\dot{m}_f(P_{fc}(t)) = a\ P_{fc}^2(t) + b\ P_{fc}(t) + c \tag{1}$$

where a, b, and c are coefficients depending on the used fuel cell.

The second Eq. (2) of the objective function is the supercapacitor equivalent hydrogen consumption ($\dot{m}_{sc}(P_{sc}(t), SOE(t))$), and it depends on supercapacitor power and supercapacitor state of energy. This equivalent consumption of hydrogen is multiplied by the factor $s(t)$.

$$\dot{m}_{sc}(P_{sc}(t), \mathrm{SOE}(t)) = s(t)P_{sc}(t)) \tag{2}$$

Minimizing the objective function allows to determine the optimal power split between the fuel cell and the supercapacitors. Furthermore, this approach must protect the supercapacitor from overcharging during the repetitive braking energy accumulation.

The optimal control problem is formulated as equivalent fuel consumption. The objective function J is given in the Eq. (3). The control action $u(t) = P_{fc}(t)$ is considered as the fuel cell power. The supercapacitor power is given in Eq. (4). The Eq. (5) is a weighting factor to achieve supercapacitor state of charge SOC regulation. Eq. (6) presents the relation between the supercapacitor state of charge and the state of energy SOE [25,26].

$$J = \int_{t_0}^{t_f} [\dot{m}_f(P_{fc}(t)) + s(t)P_{sc}(t)]\,\mathrm{d}t \tag{3}$$