An optimized energy management strategy for fuel cell hybrid vehicles

Wenxin Xiao\textsuperscript{1,2}, Lei Wang\textsuperscript{1}, Dongyin Liu\textsuperscript{3}, and Wenwen Zhang\textsuperscript{4,*}

\textsuperscript{1}Chinese-German College, Tongji University, Shanghai, China
\textsuperscript{2}Department of Electrical and Computer Engineering, Technische Universität München, Munich, Germany
\textsuperscript{3}Research Center of Control Science and Intelligent System, University of Electronic Science and Technology of China, Chengdu, China
\textsuperscript{4}College of Electronics and Information Engineering, Tongji University, Shanghai, China

*Corresponding author e-mail: zhangwenwen_1203@163.com

Abstract. Fuel cell hybrid vehicles are environmentally friendly and have good development prospects. Their energy management is very important, but there are currently few studies on this topic. In this paper, an optimized energy management strategy specifically applied to fuel cell hybrid vehicles is proposed. Fuel cell hybrid vehicles have some different characteristics from ordinary hybrid vehicles, which need to be considered in energy management. For the fuel cell to remain activated during driving, its output power must remain above a minimum power. In addition, it takes some time for the fuel cell to start up. These characteristics are considered in the vehicle model. The energy management strategy proposed in this paper maximizes energy use efficiency by controlling the SOC value of the battery. The SOC value of the battery is in the proper range during driving. At high speeds, fuel is consumed as a source of energy and the battery is charged to keep its SOC at a high level. When approaching the destination or when the vehicle is traveling at a low speed, the battery is discharged to reduce fuel consumption. Applying this strategy to the ECE-15 and EUDCL environments, the simulation results show that this optimized energy management strategy improves the energy efficiency of the fuel cell and enables the battery to operate at the appropriate power.

1. Introduction
Recently, fossil fuels such as diesel and liquefied petroleum gas have become increasingly scarce and expensive. As a supplementary energy source, hydrogen is produced from renewable resources, which makes it a worthwhile option for a sustainable fuel supply.

Through the chemical reaction of hydrogen and oxygen, fuel cells power fuel cell vehicles (FCVs). The power is used to drive the motor or to charge the battery pack. Fuel cell vehicles can be very efficient and environmentally friendly, as only water is produced during the energy supply process [1].

Proton exchange membrane fuel cells are considered to be the best choice for fuel cell vehicles due to their high power density, low operating temperature, and zero emissions [2,3].
In addition to fuel cells, lithium-ion batteries are used for energy storage in fuel cell hybrid vehicles (FCHVs). Lithium-ion batteries are widely used in portable electronic devices, electric vehicles, and power grid applications, covering tens of watt-hours to tens of megawatt-hours [4].

Under an appropriate energy management strategy, the use of hybrid power can significantly improve the performance of the entire vehicle power system in different aspects, such as the recovery of additional energy through the traction motor to improve the energy efficiency and reduce the cost of fuel cells. As an alternative for solving environmental and energy problems, fuel cell hybrid vehicles with high energy efficiency and near-zero emissions are considered to have broad development prospects [5].

The FCHV’s ability to reduce pollution emissions and save energy depends on the energy use mechanism between the fuel cell and the battery, i.e., depending on the energy allocation and energy. The energy allocation of the FCHV, which includes the construction of the system topology and the setting of the parameters of the main components, is the basis for energy management. The core issue of FCHV energy management is how to coordinate the work between the battery and the fuel cell while providing the required energy under the physical constraints of the model [6].

The methods currently used to solve automotive energy management problems are mainly divided into two categories: optimization-based and rule-based solutions.

Rezaei and Burl proposed a real-time optimal strategy based on the equivalent consumption minimization strategy (ECMS) to improve the fuel economy [7]. Wu and Hu presented a stochastic control energy management method with a Markov chain model of vehicle mobility [8]. Zhang and Xiong proposed a hierarchical control strategy for multiple energy sources to obtain better fuel efficiency [9]. Sun and Hu studied an energy management strategy using artificial neural networks to predict future speeds for better performance [10]. Ahmadi and Bathaee proposed a strategy with an offline simulation using a genetic algorithm (GA) to achieve a superior optimization strategy in terms of equivalent energy consumption, energy efficiency and state of charge (SOC) changes [11]. Trovao and Santos presented an energy management strategy using a rule-based integrated metaheuristic to obtain a solution for sharing energy and power between two sources with different characteristics [12]. Chen and Xiong studied a particle swarm optimization (PSO)-based energy management approach to minimize the total energy cost of vehicle utilization (the sum of oil and electricity) [13].

The global optimal solution is based on driving situation to achieve the lowest fuel consumption. Although the goal of the instantaneous optimal energy management strategy is optimal at all times, the system cannot achieve global optimality, and because of the large amount of computation, it is difficult to directly use it for real-time energy management. Therefore, the optimization-based strategy can only target specific driving cycles [14].

In contrast, rule-based energy management strategies are designed based on mathematical models and often do not have the priori knowledge of the intended driving cycle. They can realize real-time control and their algorithms are easy to implement, so they are widely used in practical hybrid vehicle energy management systems [15].

At present, most of the energy management strategies adopted by automobile manufacturers are based on rules. Among them, the energy management strategy proposed by Toyota is based on the following heuristics [16]:

1. If the SOC of the battery is below its minimum allowable value, the fuel cell should provide additional power to charge the battery.
2. When the vehicle speed is lower than the minimum speed, only the battery is used.
3. The motor charges the battery through regenerative braking.
4. If the maximum power of the fuel cell cannot meet the power required by the car, the battery provides insufficient energy.

This strategy has low computational complexity and is low cost, simple and easy to implement in real time [17]. However, it has the following disadvantages:

1. The static SOC threshold value is set according to the strategy, which makes it impossible to maximize the energy utilization under different vehicle conditions. This is probably not the best solution...
for a specific driving cycle [15].

2. The SOC value needs to be artificially selected or set, which relies on human experience and judgment, resulting in delay and unreliability.

In addition, battery performance is critical to the long-term operation of hybrid vehicles in terms of economic savings and energy supply. Battery aging is currently a common bottleneck for vehicles with batteries, but it is rarely considered in energy management strategies for fuel cell hybrid vehicles [18].

To address these problems, this paper proposes an improved energy management strategy. In this strategy, the energy management system use the data of a specific route to calculate accurate SOC threshold values. The goal is to minimize the total stroke fuel consumption.

The rest of this paper is organized as follows. Section 2 describes the construction process of the vehicle model and introduces the various component modules. The key parameters of each module are listed in this section. The optimized power management strategy is discussed in section 3. The core goal is to reduce fuel consumption and slow down battery aging. Section 4 compares the results of the optimized power management strategy with the Toyota Prius strategy and discusses the results. Section 5 summarizes the conclusions.

To verify the validity and rationality of the energy management strategy, a simulation is performed according to the improved strategy and the strategy adopted by the Toyota Prius. Then, the efficiency of energy utilization in both cases will be compared.

2. Model of FCHV

The fuel cell hybrid vehicle is modeled in MATLAB/Simulink. As shown in Figure 1, the vehicle model consists of a fuel cell stack, a motor model block, a vehicle dynamic control block, and an energy management block. In this model, the motor controller requires an input voltage that is higher than the output voltage of the fuel cell, so a DC/DC converter is used to convert the voltage [19].

![Figure 1. Overall vehicle model.](image-url)

2.1. The fuel-cell stack model

The power of fuel cell hybrid vehicles comes mainly from the fuel cell stacks. Similar to the role of cylinders in internal combustion engines, fuel cell stacks are also the core of the vehicles’ powertrain. The fuel cell stack model is primarily concerned with the electrical relationships (current-voltage curve and voltage-power curve). Many of the complex details of the physical model, such as the material type and blower size, are not specifically listed and are generally represented by electrical characteristics.
A group of fuel cells is connected in series to form a fuel cell stack. Obviously, the voltage of the fuel cell stack is the sum of the voltages of all the fuel cells. The voltage of these batteries is assumed to be the same so that the stack voltage can be defined as [20]:

\[ V_{fs} = n \times V_{fc} \]  

where \( V_{fs} \) is the fuel cell stack voltage, \( n \) is the number of fuel cells connected in series and \( V_{fc} \) is the cell voltage.

The value of the cell voltage can be calculated from the physical characteristics of the fuel cell [21]:

\[ V_{fc} = E_{fc} - V_{act} - V_{ohm} - V_{conc} \]  

where \( E_{fc} \) is the open circuit voltage, \( V_{act} \) is the activation voltage loss, \( V_{ohm} \) is the ohmic voltage loss, and \( V_{conc} \) is the concentration of voltage loss.

The open circuit voltage, \( E_{fc} \), can be formulated using the following equations [22]:

\[ E_{fc} = 1.229 - 8.5 \times 10^{-4} \left( T_{fc} - 298.15 \right) + 4.3085 \times 10^{-5} T_{fc} \left[ \ln \left( P_{H_2} \right) + \left( P_{O_2} \right) / 2 \right] \]  

where \( T_{fc} \) is the temperature of the fuel cell, \( P_{H_2} \) is the partial pressure of hydrogen, and \( P_{O_2} \) is the partial pressure of oxygen.

The reason for the activation voltage losses is that electrons react at the cathode, which migrates from the anode [23]. In the following Tafel equation, the activation voltage losses are represented by parameters related to the current density:

\[ V_{act} = v_0 + v_\alpha \left( 1 - e^{-i} \right) \]  

where \( v_0 \) is the voltage drop at zero current density, and \( v_\alpha \) is a constant calculated by the total cathode pressure and saturation pressure.

In this module, the consumption of hydrogen and the energy it provides must also be calculated. Hydrogen consumption can be denoted by the following equation:

\[ W_{H_2} = M_{H_2} \frac{n_{st}}{2F} \]  

where \( W_{H_2} \) is the mass of the reacted hydrogen, \( M_{H_2} \) is the hydrogen molar mass, \( n_{st} \) is the stack current, and \( F \) is the Faraday constant with a value of 96487.

The start of the fuel cell takes a certain amount of time. The fuel cell must not be below the minimum output power during engine operation; otherwise, the fuel cell will shut down. In this model, the minimum output power of the fuel cell is set to 2000 watts.

2.2. The battery model

The battery system is relatively simple compared to the fuel cell system. It consists of a series-connected lithium-ion battery that does not require control of the hydrogen and oxygen fuel. In the simulation structure of the overall vehicle model (Figure 1), the battery terminal is directly connected to the DC-DC converter, so the battery terminal voltage is equal to the DC bus voltage. The equivalent loop of a single battery model is shown in Figure 2, which is an equivalent circuit model with a voltage source and an internal resistance [24].
The terminal voltage, \( E \), of the battery pack can be expressed as:

\[
E = n(U - RI)
\]  

(6)

where \( n \) is the number of battery cells, \( U \) is the open circuit voltage, \( R \) is the battery internal resistance, and \( I \) is the current output from the battery pack.

When the battery pack needs to provide external power of size \( P \), the current generated by the battery pack can be derived from the above equivalent circuit model:

\[
I = \frac{nU - (nU)^2 - 4nRP}{2nR}
\]  

(7)

The SOC of a battery is the ratio of the current battery capacity to the maximum battery capacity, ranging from 0 to 1. The remaining battery power is known as the SOC. The SOC of the battery pack at a certain time can be calculated by the following equation [25]:

\[
SOC(t) = SOC(t_0) - \frac{1}{C_b} \int_{t_0}^{t} I_b \, dt
\]  

(8)

where \( SOC(t) \) is the state of charge of the battery at time \( t \), \( SOC(t_0) \) is the state of charge of the battery at time \( t_0 \), \( C_b \) denotes the maximum battery cell capacity. Table 1 shows the parameters used by the Battery Model.

| Name                  | Value       |
|-----------------------|-------------|
| Nominal Voltage       | 288 V       |
| Maximum Capacity      | 13.9 Ah     |
| Fully Charged Voltage | 335.2283 V  |
| Nominal Discharge     | 6.0435 A    |
| Current               | 0.20719 Ω   |
| Internal Resistance   | 12.5704 h   |
| Capacity at Nominal   |             |
| Voltage               |             |

2.3. The vehicle dynamics model

The vehicle dynamics control block is a physical model. The car model simulates the actual force of the car during driving, mainly based on the equation of traction [26]:

\[
F_{te} = F_{rr} + F_{wa} + F_{la} + F_{ad}
\]  

(9)
where $F_{te}$ is the total tractive effort, $F_{rr}$ is the rolling resistance force, $F_{wa}$ is the force required for the angular acceleration of the rotating motor, $F_{la}$ is the force required for linear acceleration, and $F_{ad}$ is the aerodynamic drag.

The rolling resistance is basically a constant value that is proportional to the weight of the vehicle, mainly due to the friction of the tires on the road surface when the vehicle is running. The rolling resistance hardly changes due to the speed of the vehicle:

$$F_{rr} = \mu_{rr}mg$$  \hspace{1cm} (10)

where $\mu_{rr}$ is the coefficient of rolling resistance, $\mu_{rr}$ is mainly determined by the tire pressure and the tire material.

$F_{wa}$ is the force that provides the angular acceleration to the tires, which can be formulated using the following equations:

$$F_{wa} = I \frac{r^2}{r^2} a$$  \hspace{1cm} (11)

where $I$ is the inertia moment of the engine rotor, $G$ is the gear ratio, $r$ is the tire radius, and $a$ is the acceleration of the vehicle.

$F_{la}$ is the force that linearly accelerates or decelerates the vehicle, which can be determined from the mass and acceleration of the vehicle:

$$F_{la} = ma$$  \hspace{1cm} (12)

The vehicle is subject to resistance from the air while driving, so the aerodynamic drag needs to be considered. This component is defined as:

$$F_{ad} = \frac{1}{2} \rho AC_d v^2$$  \hspace{1cm} (13)

where $\rho$ is the density of the air, $A$ is the frontal area of the vehicle, $C_d$ is the drag coefficient, and $v$ is the vehicle speed.

2.4. The powertrain/energy flow

The energy transfer relationships between the modules of the hybrid fuel vehicle model are shown in Figure 3.

![Figure 3. Energy flows in the FCHV model.](image)

The relationship between the energies is reflected by the following equations [26]:

$$P_{mot-i} = P_{batt} + P_{fc}$$  \hspace{1cm} (14)
where $P_{mot-in}$ is the energy supplied to the motor, $P_{batt}$ is the energy output by the battery, and $P_{fc}$ is the energy output by the fuel cell. When the battery power is negative, the battery pack is charged.

When the vehicle is running, the output power of the motor satisfies the following equation:

$$P_{mot-out} = \eta_m P_{mot-i}$$

(15)

$$P_{mot-out} = \frac{P_{fc}}{\eta_g}$$

(16)

where $\eta_m$ is the efficiency of the motor, $P_{te}$ is the energy required to move the vehicle, and $\eta_g$ is the efficiency of the gear system.

When the motor is used for braking, the efficiency works in the opposite direction, and the following equation will be established:

$$P_{mot-o} = \frac{P_{mot-in}}{\eta_g}$$

(17)

$$P_{mot-out} = \eta_g P_{te}$$

(18)

The energy values provided by the fuel cell and battery are passed to the vehicle dynamics model, and the model is simulated to obtain the results for the vehicle speed, engine speed and required drive power. These data are fed back to the power management system, which will process the data according to the power management policy. The power management system will calculate the required fuel cell and battery energy separately and pass the data to the fuel cell model and battery model. In the fuel cell model, the corresponding hydrogen and oxygen flow rates were calculated to run the simulation. The battery current and voltage amplitude were calculated in the battery model for the simulation.

3. **Optimized power management strategy**

To optimize the energy efficiency of fuel cell hybrid vehicles under specific road conditions, an optimized power management strategy is proposed in this paper. Since reducing gas fuel usage rather than charging the battery is the core goal of this strategy, the fuel cell power consumption in the simulation is the main concern.

The FCHV optimized energy management strategy should meet the following basic principles:

1. When the vehicle speed is lower than 10 km/h, as long as the battery power is sufficient, the battery is fully used to supply energy to the vehicle at the initial stage.

2. The fuel cell starts when the vehicle speed is greater than 10 km/h. The output power of the fuel cell during normal operation is always not lower than the minimum output power. At this stage, the battery works to bring its state of charge close to a target SOC. When the current SOC of the battery is less than the target SOC, the vehicle power is completely supplied by the fuel cell, and the battery is charged; when the current SOC of the battery is greater than the target SOC, the battery vehicle power is provided by both the fuel cell and the battery.

3. When the car brakes, the fuel cell maintains the minimum output power, and the battery is charged by the energy recovered from the brakes and fuel cell. When the vehicle stops, the fuel cell is turned off.

According to the latest research on vehicle batteries, maintaining a SOC of approximately 50% during driving is the best option as it increases the life expectancy of a car battery by 44-130%. By keeping the battery at 15% SOC during parking, the aging of the battery can be significantly reduced. Storing the battery at 15% SOC two days a week can extend the lifetime by more than half a year [27].

In this strategy, to reduce the gas fuel usage, the car battery should be maintained at an appropriate SOC value as often as possible to prolong its lifetime.
This strategy is mainly used for daily driving conditions. Multiple simulations were performed on the platform using the collected data on the frequently driven route. The appropriate target SOC in different driving stages is obtained by the following algorithm:

$$\text{target SOC} = \begin{cases} \text{50}\% & t < t_0 \\ \left(15 - \Delta SOC_{last\,brake}\right)\% & t \geq t_0 \end{cases}$$  \tag{19}$$

where $t_0$ is the latest time to reduce the SOC from 50% to 15%, and $\Delta SOC_{last\,brake}$ is the value added to the SOC during the last braking phase. Both parameters are obtained from the previous simulation results.

The optimized energy management strategy will be compared to the Toyota Prius’ energy management strategy. The Prius’ strategy sets the target SOC to 56%, which forces the battery to store up to approximately 56% of its battery capacity throughout the driving cycle [28].

4. Simulation results and discussion
To better simulate the daily driving conditions, sufficient driving time is considered, and both low speed and high-speed driving situations are taken into consideration. For these purposes, the driving cycle consisting of the urban driving cycle (ECE-15) and extra urban driving cycle for low power vehicles (EUDCL) is adopted in the simulation, as shown in Figure 4.

![Figure 4. Vehicle speed over the entire driving cycle.](image-url)

Figures 5 and 6 show the SOC data of the two strategies while driving over the driving cycle. For both cases, the initial SOC is set to 50%.

Figure 5 shows that the fuel tends to be used as little as possible in the case of the optimized strategy. During the urban driving cycle at low speeds, the target SOC is set low so that the battery power can be fully utilized. Then, the target SOC is set to 50% to extend the battery lifetime. At an appropriate time, the target SOC is set to a value slightly below 15% so that it can be at 15% at the end of the final brake deceleration phase.
As seen from the results, although the target SOC is set low during the urban driving cycles, the SOC during this period can be approximately 50% since the fuel cell is operated at least at the minimum power and the battery is charged during braking.

The real-time use of batteries and fuels is shown in Figures 7 and 8 for the two strategies.
By integrating the real-time use of the battery and fuel over time, the total energy consumption of the two energy types is obtained. In the optimization strategy, the total energy usage of the fuel is $5.64 \times 10^3$ kJ, and the total energy usage of the battery is $4.82 \times 10^3$ kJ. In the Prius’ strategy, the total energy usage of the fuel is $1.21 \times 10^4$ kJ, and the total energy usage of the battery is $-1.55 \times 10^3$ kJ. The negative sign indicates that the battery is charged.

In Prius’ strategy, much energy from the fuel cells is used to charge the battery, resulting in underutilization of energy. In addition, the battery will leak when the vehicle is parked, and too high a SOC will greatly shorten the battery life.

In the optimization strategy, energy from the battery is effectively utilized, and the fuel consumption is reduced by 53.4%. When the vehicle is parked, the SOC is 15%. When the vehicle is running, for nearly half of the time the SOC is approximately 50%, which will extend the life of the battery by at least 44% [27].

5. Conclusion
In this paper, an improved energy management strategy is realized for FCHVs. The model of the fuel cell hybrid car is built in MATLAB/Simulink. The vehicle model includes an energy management block, a fuel cell stack, a motor model block, and a vehicle dynamic control block.

This study simulates the energy usage of cars in ECE-15 and EUDCL environments. By using only the batteries during the start-up phase and charging the battery during the braking phase, the energy efficiency is improved. In addition, different target SOCs are set at different driving stages, which allows the vehicle to run or stop at the most suitable SOC. However, this energy management strategy is optimal when it is known to travel the entire distance, which has certain limitations. Therefore, this strategy is suitable for use in daily repeated travel sections or known destinations.

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