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# AN ADAPTED RULE-BASED METHOD ON POWER ENERGY MANAGEMENT FOR FUEL CELL VEHICLES

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## ABSTRACT
With severe environmental pollution pressures growing, research on fuel cell vehicles is increasing. Compared to electric vehicles, fuel cell vehicles do not have the constraints of driving distances. Meanwhile, the emissions of fuel cell vehicles are cleaner than the traditional vehicles. This paper takes a fuel cell bus as the research object. Based on the characteristics of fuel cell vehicles, the Dynamic Programming algorithm is used to calculate the global optimal process for typical urban conditions. The drawback of the global optimal process is that the operating conditions must be known before.As a result, it is not reasonable to use dynamic programming in real driving condition. Therefore, we propose to use an adapted power management method to deal with the actual driving conditions.

**Keywords:** Fuel cell vehicle, Adapted rule-based method, Power consumption, Dynamic programing

## NONMENCLATURE

| *Abbreviations* | |
|---|---|
| $C_{\_r}$ | rolling coefficient |
| *DP* | Dynamic programing |
| $F_f$ | Rolling resistance (N) |
| $F_j$ | gradient drag (N) |
| $F_t$ | traction (N) |
| $F_w$ | aerodynamic force (N) |
| $g$ | gravitational constant (m/s2) |
| $P_{fc}$ | Power of fuel cell(kW) |
| $P_{batt}$ | Power of battery(kW) |
| $P_{motor}$ | Power of motor(kW) |
| $I$ | Current of battery(A) |
| $U$ | Voltage of battery(v) |
| $T_{mot}$ | Torque of motor |
| $i$ | Gear ratio |
| $R$ | Radius of vehicle |
| $\eta_{batt}$ | Efficiency of battery |
| $\eta_{DC/DC}$ | Efficiency of DCDC |
| $\eta_{fc}$ | Efficiency of fuel cell engine |
| $\eta_m$ | Mechanical efficiency |
| $\rho$ | the air density |
| $A_f$ | the frontal area |
| $C_d$ | the drag coefficient of the vehicle |
| $R\_r$ | the internal resistance of the battery |
| ARBM | Adapted rule-based method |

## 1. INTRODUCTION
The development of fuel cell vehicles provides a great idea for solving traffic congestion, energy shortages and environmental pollution[1]. A lot of research on fuel cell hybrid vehicles has been carried out. For example, Li Qi has done a lot of research on fuel cell hybrid vehicles in rail vehicles[2]. For fuel cell hybrid vehicles, the power distribution between the fuel cell engine and the power battery is mainly considered. In order to solve the problem of energy distribution for hybrid vehicles, the optimal control algorithm plays a big role[3].

In this paper, the topology of fuel cell vehicles is introduced at the first part. In the second part, a vehicle model is built. Then, the dynamic programming method is introduced and the optimal control problem is carried out at the third part. After that, the CDCS method and adapted rule-based method are discussed[4]. The result for this paper is shown at the forth part. Last but not least, we give the conclusion and prospect at the last part.

## *2.* TOPOLOGY OF FUEL CELL VEHICLE
In this topology, the power of fuel cell engine are mixed with the power of battery to drive the motor. The power equation for this topology is shown as follows.

$$P_{fc} + P_{batt} = P_{motor} \tag{1}$$

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It it kowns that the dynamic response characteristics of the fuel cell that the rate of change of power cannot be excessive. When the demand power of motor exceeds the range that the fuel cell can provide, the charging and discharging of the battery can relieve these problems.

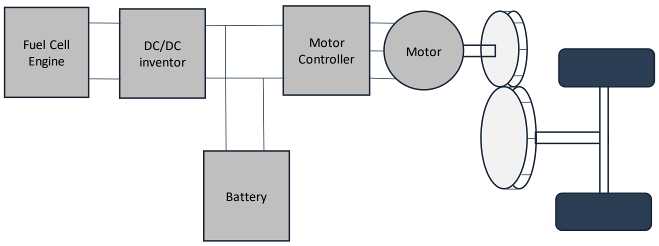


Fig 1 *Topology of fuel cell vehicle*

## 3. VEHICLE MODEL

In this part, a vehicle simulation model is built. The parameters of vehicle model are showed in Table 1.

**Table 1.** Vehicle parameters

| Specification | value |
|---|---|
| Mass [kg] | 10000 |
| Tire Radius [m] | 0.446 |
| Front Area [ $m^2$ ] | 8.16 |
| Drag_Coeff. [-] | 0.55 |
| Air_Density [kg/$m^3$ ] | 1.2 |
| Efficiency of Transmission [-] | 0.9 |
| Equviant _Coeff. [-] | 1.2 |
| C_batt [Ah] | 60 |

The longitudinal dynamics of the vehicle is given by

$$F_t = F_f + F_w + F_i + F_j \tag{2}$$

where $F_t$ is the force supplied by the motor and transmitted to the tires by means of mechanical connections, and its formulation is given by:

$$F_t = \frac{T_{mot} i_0 \eta_T}{r} \tag{3}$$

The friction force is given by:

$$F_f = mg\cos\alpha \bullet C_{\_r} \tag{4}$$

$C_{\_r}$ is the rolling coefficient, and it is given by:

$$C_{\_r} = 0.005 + \frac{1}{2.5}\left(0.01 + 0.0095 * \left(\frac{100v}{3.6}\right)^2\right) \tag{5}$$

The aerodynamic resistance $F_w$ is given by

$$F_w = \frac{1}{2}\rho A_f C_d v^2 \tag{6}$$

The road grade force $F_f$ is defined as

$$F_f = mg\sin(\alpha) \tag{7}$$

The electric consumption equation of the vehicle is given by:

$$I = \frac{U - \sqrt{U^2 - 4 \bullet R\_r \bullet P_{batt}}}{2r} \tag{8}$$

## 4. DYNAMIC PROGRAMMING

Dynamic programming is a powerful numerical method for solving optimal control problems. Many studied have been carried out in recent years. Only if all future disturbance and reference inputs are known, the optimal controller can be found[5].

The states of Dynamic programming are the required power of fuel cell engine and the state of charge(SoC) of battery. In case of the rapid change of the power of fuel cell engine, the action is selected as the change of fuel cell power[6].

$$\min_{u_k \in U_k} \sum_{k=0}^{N-1} \Delta P\left(x_1, x_2, u_k\right) \tag{9}$$

s.t.

$$x_{1_{k+1}} = T_s x_{2_k} + x_{1_k} \tag{10}$$

$$x_{2_{k+1}} = T_s u_k + x_{2_k} \tag{11}$$

$$x_{1_{N\min}} < x_{1_N} < x_{1_{N\max}} \tag{12}$$

$$x_{2_{N\min}} < x_{2_N} < x_{2_{N\max}} \tag{13}$$

$$u_{\min} < u_k < u_{\max} \tag{14}$$

$$N = 1 + \frac{t_0}{T_s} \tag{15}$$

## 5. ADAPTED RULE-BASED METHOD

As dynamic programming is a method to solve the optimal control problem, the driving condition must be known before. So dynamic programming can not be used in the real driving condition.

In this part, CD-CS method is introduced. Based on the CD-CS method, an adapted rule-based method (ARBM) is proposed.

The CDCS method can be described as follows. When the SOC is below a low-level limited value, which means the battery needs to be charged. When the SOC higher than a high-level value, which means the battery needs to discharge. At the first condition, fuel cell engine provides power for the battery to charge immediately. Meanwhile, the power required to drive the vehicle is also provided by the fuel cell. When the maximum power of the fuel cell is still unable to meet the driving conditions, the output power needs to be reduced.

The adapted rule-based method considers the average value of five step times into consideration. The previous require power makes sure that the power of fuel cell engine will not change rapidly. With the continuity of driving conditions, it will be less power consumption when driving[7].

$$\delta = \frac{1}{n}\sum_{i}^{n=5} P_{fc}(k-i) \tag{16}$$

Considering the power requirements of the first five simulation steps of the vehicle, the energy distribution between the fuel cell engine and the power battery is calculated by the mean value and variance, which can ensure that the power change of fuel cell will be not rapid. In this way, the historical vehicle speed information can be used to estimate the energy distribution ratio. After calculation, the energy can be allocated using the following formula.

$$P_{fc} = k_1 \bullet \delta Pm + k_2 \bullet P_{fc\_CDCS} \tag{17}$$

## 6. DRIVING CONDITION

In this paper, the driving condition is changed from the standard China city driving condition. The max speed of the bus is 60km/h. As a result, we decreased the last 20 seconds, which is not available for the bus in this paper. The changed driving condition is shown in figure 2. We can calculate out the required power of the motor by the driving condition. And the required power of motor is shown in figure 3.

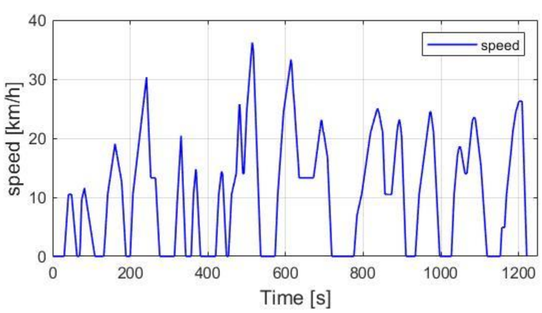

Fig 2 *Driving condition*

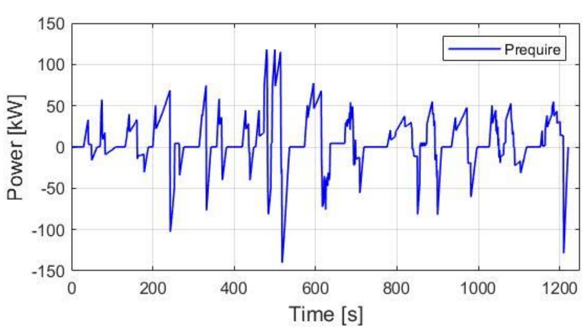

Fig 3 *The required power of motor*

## 7. RESULTS

The results of the power consumption of fuel cell engine of DP and ARBM are shown in figure 4. From figure 4, we can see that at the beginning of the driving condition, the DP result is higher than the ARBM result. For considering the global power consumption, fuel cell engine needs to charge the battery in advance, in case of

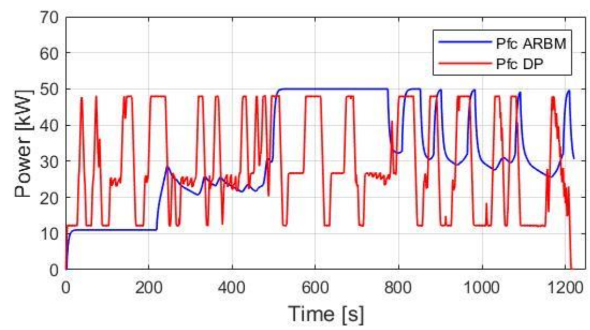

Fig 4 *The comparison of $P_{fc}$*

using more energy when the driving condition is heavy.

The results of SOC for both method are compared in figure 5. From figure 5, we can see that the SOC is nearly the same in the end. Besides, the trends of both SOC are similar. The comparisons of power consumption and the end state of charge are shown in table2.

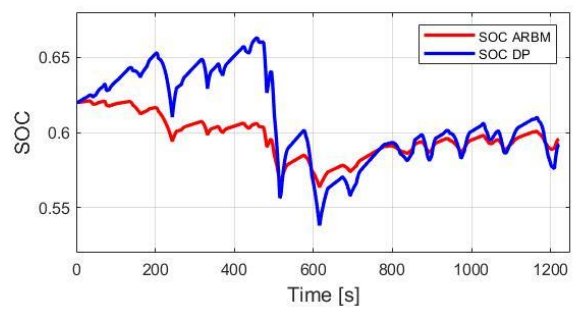

Fig 5 *The comparison of SOC*

Table 2. The comparisons of DP and ARBM

| Method | Hydrogen Cost | Rest of SOC |
|---|---|---|
| DP | 9.75kWh | 0.5920 |
| ARBM | 10.63kWh | 0.5959 |

## 8. DISCUSSION

It can be seen from the fuel cell efficiency curve that the fuel cell has high efficiency around low power. According to the results of dynamic programming, it can be seen that the fuel cell engine mainly works below 30 kW. Since the fuel cell engine is the most efficient at 11 kW, it is obvious that the dynamic programming results are around at 11 kW for most time.

Based on the ARBM method, since the starting time cannot predict the future working conditions, under the constraint of the battery SOC, the initial working is about 11 kW. When the operating conditions change more severely, there is a dynamic charge-discharge relationship between the fuel cell and the power battery. As can be seen from Figure 4, the overall trend of the SOC is generally consistent, so it can be stated that the ARBM method is feasible in the actual process.

## 9. CONCLUSIONS

In this paper, an optimal control problem is proposed for fuel cell vehicle. For solving this problem, dynamic programming method is used for the China City driving conditions. But for real driving condition, it can not be used for the reason that the driving condition is not used in advance. Based on the CD-CS method, an adapted rule-based method is proposed for the real driving condition. As a result, the power cost of fuel cell engine is only 7.8% higher than the dynamic programming, which means the ARBM can be used in the real driving conditions.

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