Energy Management Control Strategy Optimization of Full Power Fuel Cell Vehicle Based on Wavelet Transform

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Abstract. With the development of fuel cell technology, full-power fuel cell vehicles have gradually appeared on the market. Although the configuration of hybrid system can solve part of the durability problem caused by starting and stopping conditions, it faces the durability problem caused by variable load conditions. In this paper, wavelet transform is used to optimize the energy management strategy of a full-power fuel cell vehicle, the fuel cell is responsible for the low frequency part of the total output power, and the battery is responsible for the high-frequency part of the total output power. Thereby the durability of the fuel cell is optimized. In addition, this study also compares the power change rate before and after optimization under different cycling conditions, which illustrates the adaptability of this method. And the more aggressive of the drive pattern for test cycle, the more obvious the effect of this method on improving the durability of fuel cells.

1. Introduction

With the development of fuel cell vehicle technology, full-power fuel cell vehicles gradually appear on the market. Full-power fuel cell vehicles are mainly driven by fuel cells with small capacity power batteries. Under this kind of combined power configuration, the power distributed to the fuel cell changes at a high rate, which will seriously affect the life of the fuel cell.

In this paper, an energy management strategy based on wavelet transform is proposed to improve the service life of fuel cells. Wavelet transform is an ideal tool for signal analysis and processing. It can also extract signals with different frequency bandwidths from the original signal. Compared with Fourier transform, wavelet transform can extract information in both time domain and frequency domain. In order to eliminate damage of power source itself caused by large frequency fluctuation of power output, wavelet transform tool is often used. Especially in the field of energy system and energy management strategy, has been widely used.

The paper is organized as follows: the power characteristics and durability mechanism of full power fuel cell is analysed in section 2. Section 3 presents the wavelet transformation process, selection of wavelet and decomposition scale, then a new energy management strategy is put forward. The superiority of the optimized strategy is verified in section 4 by comparing the voltage decay rate of fuel cell. Then adaptability of this method are illustrated under different driving cycling conditions. Finally, the conclusion and work directions in future are illustrated in section 6.

Since the power type battery for hybrid electric vehicles can accept a high power fluctuation range, and the vehicle configuration only has two power sources which means no ultra-capacitors, this energy management strategy does not focus on the power battery life.
2. Analysis of fuel cell output characteristics
The test vehicle under this study is a full-power type fuel cell vehicle. According to the OEMs’ definition, the features of full-power fuel cell vehicle can be described as follows: external output power of the fuel cell is more than 80kW, the hydrogen storage capacity is more than 5kg, and the power battery capacity is less than 2kWh. The vehicle system configuration studied in this paper is shown in figure 1. The vehicle has two power sources, which includes fuel cell system and high voltage battery pack. The output terminal of the fuel cell is one-way DCDC, which can control the work point of fuel cell. The output end of the battery pack is a two-way DCDC, which can raise the battery pack voltage to the electric drive system voltage platform. When the vehicle is in the braking state, energy can be recovered to the battery pack.

![Figure 1. System configuration of full-power fuel cell vehicle.](image)

For the fuel cell vehicle configuration shown in figure 1, the design of energy management strategy mainly includes two parts: the fuel cell system start-stop strategy, and the power distribution method of the battery and the fuel cell.

![Figure 2. Energy management process of full power fuel cell vehicle](image)

Commonly, the energy management strategy used by full-power fuel cell vehicles is shown in figure 2, which adopts a rule-based and map-based approach. The driver's power demand is calculated based on the velocity and the opening of the accelerator pedal. And the total power demand is obtained by adding the power demand of the accessories. At the same time, the SOC, temperature and other information of the battery pack are read, and the power distribution Map of the battery pack is inquired for power distribution. In order to avoid low working efficiency range of fuel cell, the battery drive mode is designed. The battery pack drives the vehicle alone when the total power demand is low, so as to avoid the fuel cell working in the low power and low efficiency area. When the required power is higher than the minimum threshold, power is allocated according to the fuel cell system and battery pack distribution map.

In order to analyse the external output characteristics of fuel cell system under rule based energy management strategies, the test vehicle with the control strategy shown in figure 2 is tested on the chassis dynamometer at NEDC cycle conditions, and the power analyser is used to collect the output power of fuel cell system and battery pack, as shown in figure 3. In the vehicle start-up phase and the braking energy recovery phase, the power output or recovery power is generated by the battery pack,
while the output power of the two power sources is distributed based on the fuel cell efficiency under medium and high loads. Under the rule based energy management strategy, the battery pack SOC is ensured to work within the appropriate range, and the hydrogen consumption level is reduced to a certain extent.

![Figure 3. Output power distribution of fuel cell system and battery pack.](image)

Fuel cell system design process should consider both economy and durability. The life of full-power fuel cells is a major challenge. When vehicle starts and stops frequently, it is easy to produce high potential and lead to the corrosion of catalyst. In addition, sharp deceleration and acceleration causes rise and fall of potential repeatedly, which means the dissolution and precipitation of the catalyst, leading to the increase of specific surface area and the decrease of activity of platinum particles.

![Figure 4. Power change rate of fuel cell system before optimization.](image)

Hybrid system configuration is used to solve the problem of start and stop condition to a certain extent. But for full power fuel cell vehicle, due to the small capacity of battery pack, battery pack can’t stay in high power output state for long time for battery pack SOC balanced. So there is still a situation that fuel cell power output change rate at a high level [1]. Figure 4 shows the change rate of fuel cell output power under NEDC driving cycles. Considering the durability, the fuel cell output characteristics of this test model need to be optimized.

In order to solve the problem, this paper extract the high frequency parts in the driver's demand power by using wavelet transform method. For high frequency parts, battery pack is used to output which is not sensitive to high frequency power and has the rapid dynamic response. For low frequency parts, fuel cell system is used to output to ensure the function requirements of fuel cell system as main source of power. Considering the high frequency of dynamic response of the battery pack in the paper, this control method is more suitable for hybrid systems equipped with power type battery pack. This paper mainly deals with the durability problem of full-power fuel cell system under variable load conditions.

3. Energy management strategy based on wavelet transform

Wavelet analysis is a general term used in a series of mathematical methods of signal processing, which is widely used in mathematics, physics, engineering and other fields. Since the vehicle internal signals are discrete signal, the discrete wavelet transform is adopted. The wavelet transform of the signal can be defined as:
\[
W_x(t) = x(t) \ast \phi_x = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} S(t) \phi \left( \frac{t-n}{s} \right) \, du
\]  

(1)

Where \( s \) is the scale factor, \( \phi_x \) is the dilatation of basic wavelet \( \phi(t) \) based on scale factor \( s \). And \( s = 2^j \), \( j \) is a natural number. So the wavelet transform is Dyadic wavelet transform.

Mallat algorithm is commonly used to calculate the Dyadic wavelet transform as follows:

\[
S_{2j}x(n) = \sum_{k \in \mathbb{Z}} h_k S_{2j-1}x(n-2^{j-1}k)
\]  

(2)

\[
W_{2j}x(n) = \sum_{k \in \mathbb{Z}} g_k S_{2j-1}x(n-2^{j-1}k)
\]  

(3)

Where \( S_{2j} \) is smoothing operator, \( W_{2j}x(n) \) is the wavelet transform of digital signal \( x(n) \). Low pass filter and high pass filter can be expressed as:

\[
H(\omega) = \sum_{k \in \mathbb{Z}} h_k e^{-ik\omega}
\]  

(4)

\[
G(\omega) = \sum_{k \in \mathbb{Z}} g_k e^{-ik\omega}
\]  

(5)

Where \( h_k \) and \( g_k \) are coefficient of low pass filter and high pass filter respectively.

The wavelet transform of signal mainly include two phases: decomposition and reconstruction. In the decomposition phase, approximation and detail coefficients are produced as follows:

\[
cA_1(k) = \sum_n h_0(n-2k)cA_0(n)
\]  

(6)

\[
cD_1(k) = \sum_n h_1(n-2k)cA_0(n)
\]  

(7)

Signals can be represented by coefficients,

\[
x(t) = \sum_k cA_0 \phi_{j,k}(t) = \sum_k cA_1 \phi_{j-1,k}(t) + \sum_k cD_1 \phi_{j-1,k}(t)
\]  

(8)

After repeated operations on the approximate coefficient, n-layer decomposition can be carried out as follows:

\[
x(t) = A_1(t) + D_1(t)
\]

\[
= A_N(t) + D_N(t) + D_{N-1}(t) + \ldots + D_1(t)
\]  

(9)

As for the reconstruction of wavelet transform, the steps are reversible. The approximate coefficient and detail coefficient are used to reconstruct the signal, in which those through the high-pass filter are the approximate value, while those through the low-pass filter are the detail value. The first decomposition can be expressed as:

\[
A_1 = \begin{bmatrix}
a_{1(1)} \\
a_{1(2)} \\
a_{1(3)}
\end{bmatrix}
\begin{bmatrix}
x(1) x(2) \ldots x(N) \\
x(3) x(4) \ldots x(N+2)
\end{bmatrix}
\begin{bmatrix}
H \end{bmatrix}
\]  

(10)

\[
D_1 = \begin{bmatrix}
d_{1(1)} \\
d_{1(2)} \\
d_{1(3)}
\end{bmatrix}
\begin{bmatrix}
x(2(k-1) + 1) x(2(2k-1) + 2) \ldots x(2(2k-1) + N)
\end{bmatrix}
\begin{bmatrix}
G
\end{bmatrix}
\]  

(11)

\[
H = \begin{bmatrix}
h(1) \\
h(2) \\
h(k)
\end{bmatrix}
\begin{bmatrix}
g(1) \\
g(2) \\
g(k)
\end{bmatrix}
\]  

(12)

The decomposition of layer j can be expressed as:
The wavelet bases adopted by wavelet transform include Haar wavelet bases, Daubechies wavelet bases, Maxican Hat wavelet bases, etc. [2]. This study selected Haar wavelet as the wavelet base. Compared with other wavelet base, Haar wavelet have the shortest length of filter in time domain, moreover the wavelet transform and its inverse transform are equal. So at the real vehicle applications, the Haar wavelet has the highest code execution efficiency, and normal single chip can handle it. In the online vehicle energy management is feasible.

The selection of wavelet decomposition level is related to the application scenario. In this study, wavelet transform is used to extract the low-frequency signal corresponding to fuel cell output, and the remaining high-frequency signal corresponding to power battery output. In the wavelet transform, the relationship between the sampling frequency \( f_s \) and the target frequency \( f_c \) can be described as follows [3][4]:

\[
f_c = \frac{N_f}{2^n} = \frac{f_s}{2^{n+1}}
\]

Where \( N_f \) is the Nyquist frequency. Therefore, the approximate signal (low frequency part) in the wavelet transform includes the following frequency range:

\[
[0, f_c] = \left[0, \frac{N_f}{2} + 1\right]
\]

According to the above formula, it can be known that the level of wavelet transform needs to satisfy the following formula:

\[
n = \text{Rounddown}[\log_2(f_c/f_s) - 1]
\]

Considering that Haar wavelet also has a lot of detail loss after filtering, this paper adopts three-level wavelet scale according to the above formula. In addition, according to the difference of power sources, the wavelet decomposition scale can be appropriately changed to obtain the best processing results.

Through Haar wavelet transform, the original demand power signal is decomposed into appropriate signal (low frequency part) and detail signal (high frequency part). Then the obtained reference signal continues to pass through the filter and the second level decomposition is carried out. Repeat this process until the third order decomposition is completed. After the decomposition, the reconstruction is carried out, and the reconstruction process is the inverse process of decomposition. The schematic diagram of decomposition and reconstruction of the haar wavelet is shown in the following figure 5.

**Figure 5.** Decomposition and reconstruction of haar wavelet.

The following power distribution characteristics are extracted. Where, the power output characteristics of the fuel cell can be depicted as:

\[
P_{fc} = A_f(t)
\]

The expression of the power output characteristic of battery pack is:
\[ P_{\text{bat}} = D_1(t) + D_2(t) + D_3(t) \] (19)

The driver’s demand power is expressed as:
\[ P_{\text{req}} = A_3(t) + D_1(t) + D_2(t) + D_3(t) \] (20)

According to the above analysis, the fuel cell demand power obtained by wavelet transform has the characteristics of low frequency, while the battery pack demand power has the characteristics of high frequency. So the durability of the fuel cell is optimized.

4. Comparative analysis

In order to validate the superiority of control strategy based on wavelet transform, the vehicle NEDC driving cycles tests are carried out where the control strategy above chapters is used and the battery drive mode enter and exit conditions doesn’t change. Test results are shown in figure 7. After the optimization of wavelet transform, the fluctuation of fuel cell power output is decreasing. According to the energy accumulated of the battery pack output, figure 6 illustrates the battery pack SOC is still in the appropriate work window, showing that the optimized energy management strategy is still satisfied with the requirements of the full power fuel cell vehicles.

![Figure 6. Accumulation of battery pack energy consumption before and after wavelet transform optimization.](image)

Figure 7 compares the output power change rate of fuel cell before and after the optimization of energy management strategy. The figure shows that change rate of fuel cell power after the optimization of wavelet algorithm is significantly lower than that before the optimization.

![Figure 7. Fuel cell output power before and after wavelet algorithm optimization.](image)

In order to further quantitatively analyse the durability improvement effect, this study compares the voltage decay rate generated by a single cycle under two energy management strategies.
One of the main factors influencing the deterioration of fuel cell is the drastic change of operating load, so an empirical formula for describing the voltage decline rate generated by the drastic change of operating load is introduced. The study shows that the voltage decay rate corresponding to the standard deviation of the single cell output power is 225 μVh\(^{-1}\), and the decay rate is 10 μVh\(^{-1}\) under steady-state conditions. There is a relationship between the standard deviation of the single cell power change within 5s and the decay rate of the single cell voltage as follows [5]:

$$\frac{\partial u_{\text{decay}}}{\partial t} = -\frac{k}{3600} \left[225\sigma(P_f^{t-1}, P_f^{t-2}, P_f^{t-3}, P_f^{t-4}) + 10\right]$$ (21)

Where $\partial u_{\text{decay}}/\partial t$ is single cell voltage decay rate, $\sigma$ is the standard deviation function, $t$ is the current time of driving cycling, $P_f^t$ is output power at $t$, $k$ is the coefficient of different types of fuel cell stacks, in this paper, $k$ is 1.

Through calculation of the empirical formula, the single fuel cell voltage decay rate is calculated at NEDC driving cycle. As shown in figure 8, after the optimization of energy management strategy based on wavelet transform, the single fuel cell voltage decay rate is significantly decreased. Before optimization, the single fuel cell voltage decay is 14.5 μV, and after optimization, the single fuel cell voltage decay is 10.6μV, which voltage decay rate is reduced by 26.7%. The effect for durability is obvious.

**Figure 8.** Single fuel cell voltage decay rate before and after wavelet algorithm optimization.

5. **Adaptability analysis of driving cycles**

NEDC driving cycle is steady state conditions, which can’t represent the real driving conditions of vehicles. In order to verify the applicability of the control strategy based on wavelet transform, this study carries out a comparative analysis of CLTC driving cycle.

Based on same test method with NEDC driving cycle, the fuel cell power output change rate and single fuel cell voltage decay rate are compared before and after optimization as shown in figure 9 and figure 10. Under CLTC driving cycle, the single fuel cell voltage decays 61.4μV before the optimization. And after optimization, the single fuel cell voltage decays 49.2μV, reducing the voltage decay by 19.7%.

**Figure 9.** Power change rate of fuel cell before and after wavelet algorithm optimization under CLTC driving cycle.
Figure 10. Voltage decay rate of single fuel cell under CLTC driving cycle.

By comparing power change rate of fuel cell, instantaneous conditions have a larger standard deviation than steady state conditions. Application of wavelet transform for energy management can improve fuel cell durability significantly, and the more aggressive of the driving cycle, the more obvious the improvement effect of fuel cell durability.

6. Summary
Based on wavelet theory, this paper proposes an energy management strategy, which can solve the situation that full power fuel cell vehicle power output too fast, and optimize the durability of the fuel cell. The specific conclusions are as follows:

(1) The original energy management strategy of the test vehicle can guarantee the fuel economy and solve the durability problem caused by frequent stops and starts to a certain extent, but the power output change rate problem during the driving can’t be solved.

(2) Adopting the wavelet transform, the fuel cell is responsible for low-frequency output as the main energy source, while the battery pack is responsible for high-frequency part as the auxiliary energy source, which can improve the durability of the fuel cell. Under one NEDC driving cycle, the single fuel cell voltage decay can be optimized from 14.5 μV to 10.6 μV.

(3) According to validation under CLTC driving cycle, the strategy based on wavelet transform has a good adaptability. On account of instantaneous driving condition has larger standard deviation of velocity, optimization effect is more obvious under instantaneous driving condition.

(4) Due to use of power type battery pack, to a certain extent, the impact of long time output or absorption of high frequency power on the durability of the battery pack is considered. In the future, the battery pack control strategy will be further studied to ensure the battery pack life.

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