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Frequency Decoupling-Based Energy Management Strategy for Fuel Cell/Battery/Ultracapacitor Hybrid Vehicle Using Fuzzy Control Method

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ABSTRACT In order to extend fuel cell lifespan and improve fuel economy of electrical hybrid vehicle with fuel cell/battery/ultracapacitor (FCHEV), a frequency decoupling-based energy management strategy (EMS) for FCHEV using fuzzy control method is proposed. In detail, firstly, according to different characteristics of energy sources, required power of FCHEV is decomposed into three frequency ranges based on Harr wavelet transform and an adaptive-fuzzy filter. Secondly, based on the proposed frequency decoupling, the obtained three frequency required power is supplied by fuel cell-battery and ultracapacitor, respectively, which can guarantee power performance of vehicle and reduce pressure and power fluctuation on fuel cell and battery. Thirdly, for improving fuel economy, one fuzzy controller is proposed to split the power between fuel cell and battery. Finally, the proposed strategy in this paper is verified by advisor-simulink and experimental bench. Simulation and experimental results show that the proposed EMS can effectively reduce impact of power fluctuations on fuel cell, extend its lifespan and reduce fuel consumption on 7.94% compared to equivalent consumption minimization strategy.

INDEX TERMS Fuel cell electric vehicle, energy management strategy, fuzzy control, frequency decoupling, fuel economy.

NOMENCLATURE

FCHEV	Electrical hybrid vehicle with fuel cell/battery/ultracapacitor
EMS	Energy management strategy
SOC	State of charge
v	Vehicle speed
F_t	Traction force
F_f	Friction resistance with road surface
F_w	Aerodynamic drag force
F_i	Gravity force
F_j	Vehicle accelerate force
f_r	Rolling resistance coefficient
m	Vehicle mass
g	Gravity constant
α	Road angle
C_d	Aerodynamic drag coefficient
A	Vehicle frontal area
ρ	Air density
δ	Conversion coefficient of vehicle rotating mass
P_{req}	Required power of the vehicle
η_{motor}	Efficiency of the electric motor
η_{fc}	Global efficiency of fuel cell system
P_{fc}	Fuel cell power

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P_{H2}	Theoretical power
P_{au}	Auxiliary components power
η_{th}	Thermodynamic efficiency
η_{util}	Fuel utilization efficiency
η_{ind}	Individual efficiency
V_b	Battery output voltage
E_b	Battery open voltage
R_b	Internal resistance
i_b	Battery current
SOC_b	Battery SOC
SOC_1	Initial battery SOC
η_b	Battery charge and discharge efficiency
Q_b	Battery nominal capacity
V_u	Ultracapacitor terminal voltage
E_u	Capacitor voltage
R_c	Equivalent resistance
i_c	Capacitor current
SOC_u	Ultracapacitor SOC
$V_{uc,max}$	Ultracapacitor maximum voltage
P_{fc_b}	Fuel cell and battery power
${P_{fc}}^{ref}$	Fuel cell reference power
T	Time constant of the low-pass filter
f_s	Regulating frequency
FC	Fuzzy controller
${SOC_u}^{ref}$	Ultracapacitor reference SOC
f_s'	Final corrected regulating frequency
Δf_s	Adjusting frequency increment
k	Regulatory factor
DWT	Discrete wavelet transform
s	Original signal
λ	Scale parameter
u	Position parameter
W	Wavelet coefficient
S_0	Approximation part
HWFET	Highway Fuel Economy Test
UDDS	Urban Dynamometer Driving Schedule
NEDC	New European Drive Cycle
m'_{H2}	Equivalent hydrogen consumption of FCHEV
ρ_{H2}	Hydrogen chemical energy density
f_b	Equivalent factors of battery
f_u	Equivalent factors of ultracapacitor
ΔSOC_b	Indexed value of the difference between final and initial SOC_b
ΔSOC_u	Indexed value of the difference between final and initial SOC_u

I. INTRODUCTION

With continuously increase of vehicle production and retention, environment pollution and shortage of natural resources become more serious [1]–[4]. Considering characteristics of fuel cell in zero emissions, higher energy density, fuel cell electrical hybrid vehicles equipped with auxiliary power sources of battery/ultracapacitor are proved to be one alternative and promising solution [5]–[8]. As for electrical hybrid vehicle with fuel cell/battery/ultracapacitor (FCHEV), due to different features of three power sources, it is necessary and crucial to design an effective and feasible EMS that can coordinates power flow to refine fuel economy, extend fuel cell lifespan and improve power performance of vehicles.

In recent years, many results on energy management strategies (EMSs) for FCHEVs have been obtained. In general, the proposed strategies can be categorized into two main approaches: rule-based strategy [9]–[11] and optimization-based strategy [12], [13]. Rule-based energy strategies are developed based on simple rules or maps extracted from optimized algorithms like dynamic programming algorithm [14]. In [9]–[11], in order to improve the FCHEV fuel economy, rule-based EMSs are proposed to maximize the output net power by employing the charge and discharge limits of power capabilities and residual capacity of the battery and ultracapacitor. For the optimization-based strategy, the main idea lies in minimizing a pre-defined cost function within feasible constraints such as convex optimization [15], model-predictive control [16], equivalent consumption minimization strategy (ECMS) [17] and other optimization algorithms [20], [21]. For example, In [22], the dynamic programming strategy is presented to realize optimal power splitting for FCHEV energy sources to reduce system hydrogen consumption cost and electricity price of different hybrid propulsion systems.

Due to nonlinear characteristic and difficulties in building accurate model of FCHEV system, control effect of traditional control theory is limited [23], [24]. In terms of dealing with this issue, fuzzy control method is regard as one promising and effective way thanks to its independence of a full mathematical plant model [25], [26]. For the EMS of FCHEVs, fuzzy control can guarantee energy sources operate in their optimal modes. In [27], in order to protect the battery from overcharging during repetitive braking energy accumulation and improve the battery lifetime, a real-time fuzzy control method is employed to design EMS. However, the fuzzy control rules rely on a lot of engineering experience, which cannot ensure the optimality of fuzzy controller. So many researches combine fuzzy control with other control methods. In [28], an adaptive control approach with fuzzy parameter tuning is proposed for fuel cell/battery vehicles, where fuel cell output can catch up with load power more smoothly effectively. In [29], a fuzzy controller with low pass filter is proposed to prolong the fuel cell lifetime and decrease the hydrogen consumption. In [30], EMS based on the Haar wavelet transform (WT) and fuzzy control is proposed to route the positive low-frequency content of required power into the fuel cell system and its high frequencies into the battery by considering both fuel economy and fuel cell durability.

Although the similar methods of combination of fuzzy control and WT/filter have been utilized for hybrid vehicles, they are mostly used in the energy management of fuel cell/battery or fuel cell/ultracapacitor hybrid vehicles. And the influence of load fluctuation on fuel cell system cannot be minimized. Meanwhile, the balance between fuel economy and lifespan of fuel cell is important for improving the whole performance of vehicles. Through designing EMSs to obtain the balance, rapid transient of power requirement of vehicle operation can be avoided, which means that it can prolong the lifespan of fuel cell internal electrochemical structure.

Therefore, motivated by [27]–[30], in this paper, a frequency decoupling-based EMS using fuzzy control method is proposed. The contribution and motivation of this paper are summarized as follows:

1) According to different characteristics of energy sources, required power of FCHEV is decomposed into three frequency ranges based on Harr wavelet transform and an adaptive-fuzzy filter, which makes full use of three energy sources advantages.

2) An adaptive-fuzzy filter is designed to adjust ultracapacitor output power such that it can be adaptive to required power and ultracapacitor SOC, which guarantees rapid response of power demand and maintains ultracapacitor SOC in a predefined range.

3) In order to maintain battery SOC in a predefined range and reduce hydrogen consumption, another fuzzy controller is designed to be combined with Harr wavelet transform to determine fuel cell power for guaranteeing fuel cell can work in its optimal efficient range.

The rest of this paper is structured as follows. System modeling of FCHEV is introduced in Section II. In Section III, main results including the adaptive low-pass filter based on fuzzy control, power sharing algorithm based on Harr wavelet transform and fuzzy controller are addressed to split power among fuel, battery and ultracapacitor for FCHEV. Section IV presents the simulation results to confirm effectiveness of the proposed design scheme. Conclusions of this paper are drawn in Section V.

II. MODELING OF THE FCHEV

In this paper, FCHEV structure consisting of fuel cell/battery/ultracapacitor is shown in Figure 1. A battery/ultracapacitor hybrid energy storage system is employed to provide supplemental power for supporting fuel cell for the vehicle architecture shown in Figure 1. The fuel cell and ultracapacitor parallelly connect DC bus by a unidirectional DC/DC converter and a bidirectional DC/DC converter, respectively. Battery is directly linked to the DC bus to maintain DC bus voltage.

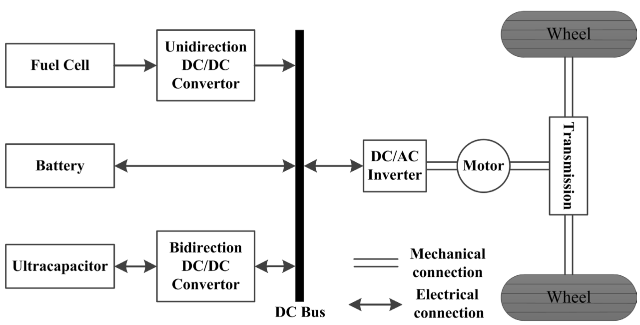


FIGURE 1. FCHEV structure.

A. MODELING OF THE VEHICLE

EMS proposed in this paper mainly deals with the vehicle demand power and distributes it to three energy sources to improve the vehicle performance. Vehicle model is established to calculate electric power required by hybrid power sources to meet a given speed v. Traction force is calculated based on the required vehicle speed, which can be described as follows [31], [32]:

$$\begin{cases} F_t = F_f + F_w + F_i + F_j \\ F_f = f_r mg\cos\alpha \\ F_w = 0.5 C_d A \rho v^2 \\ F_i = mg\sin\alpha \\ F_j = \delta m \dfrac{dv}{dt} \end{cases} \tag{1}$$

where F_f is friction resistance with road surface, F_w is aerodynamic drag force, F_i is the gravity force when the vehicle driving on non-horizontal roads, F_j is the force required to accelerate the vehicle and α is the road angle. Detail parameters of the vehicle model are listed in Table 1. Given the traction force, the required power P_{req} can be calculated by following equation:

$$P_{req} = \begin{cases} F_t \cdot v/\eta_{motor} & F_t > 0 \\ F_t \cdot v \cdot \eta_{motor} & F_t < 0 \end{cases} \tag{2}$$

where η_{motor} is the efficiency of the electric motor.

TABLE 1. Parameters of the vehicle model.

Parameter	Value
Vehicle mass, $m(kg)$	1113
Gravity constant, $g(m/s^2)$	9.8
Rolling resistance coefficient, f_r	0.6
Aerodynamic drag coefficient, C_d	0.3
Vehicle frontal area, $A(m^2)$	1.75
Air density, $\rho(kg/m^3)$	1.22
Conversion coefficient of vehicle rotating mass, δ	1.3

B. MODELING OF FUEL CELL

The fuel cell as the main power source for the FCHEV transforms chemical energy into electrical energy through chemical reaction between hydrogen and oxygen. The power module includes a 30 kW fuel cell stack module, an air delivery module, and a cooling module. The global efficiency of the fuel cell system η_{fc} is given by the following equation [33]:

$$\eta_{fc} = \frac{P_{fc}}{P_{H2}} \tag{3}$$

where P_{fc} is the output net power supplied by the fuel cell system, and P_{H2} is the theoretical power associated with the hydrogen flow consumption in fuel cell system shown as follows:

$$P_{H2} = \frac{P_{fc} + P_{au}}{\eta_{th} \cdot \eta_{util} \cdot \eta_{ind}} \tag{4}$$

where P_{au} is the power demanded by the auxiliary components of fuel cell system, η_{th} is the thermodynamic efficiency, η_{util} is the fuel utilization efficiency and η_{ind} is the individual efficiency of fuel cell, defined as the ratio between fuel cell voltage and the standard state reversible voltage.

As for the global efficiency η_{fc}, it is shown in Figure 2 as the net power varies, from which high efficiency region of fuel cell system is chosen about from its 1/6 rated power point to 2/3 rated power point in this paper. The objective of this paper is to make fuel cell system operate in this high region, where FCHEV can achieve good fuel economy by reducing hydrogen consumption.

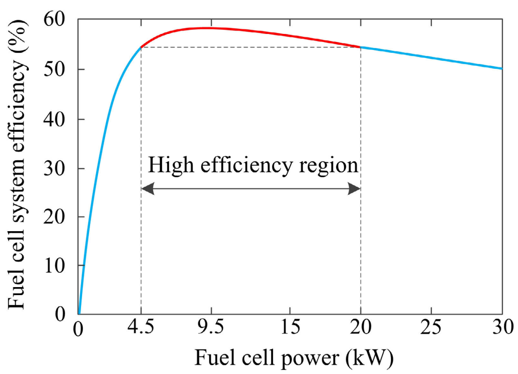


FIGURE 2. Fuel cell system efficiency versus fuel cell power.

C. MODELING OF BATTERY

Rint model is selected to analyze output characteristics of battery in this paper. Battery is simplified as a voltage source and an equivalent resistance shown in Figure 3(a). Battery SOC is an important parameter of EMS and it should be maintained in an appropriate range to avoid overcharge and over discharge of the battery. The battery output voltage and SOC can be expressed as follows [34]:

$$V_b(t) = E_b(t) - R_b i_b(t) \tag{5}$$

$$SOC_b(t) = SOC_1 - \eta_b \int \frac{i_b(t)}{3600 Q_b} dt \tag{6}$$

where V_b, E_b, R_b, i_b denote battery output voltage, battery open voltage, internal resistance, battery current, respectively, SOC_b is the battery SOC, SOC_1 is initial battery SOC, η_b is charge and discharge efficiency of battery, and Q_b is the battery nominal capacity.

D. MODELING OF ULTRACAPACITOR

To analyze performance of the ultracapacitor, ultracapacitor is modeled as a capacitor and an equivalent resistance as shown in Figure 3(b). Capacitor represents ultracapacitor performance at discharge and charge state and resistance represents the ultracapacitor ohmic losses. Ultracapacitor should supply large amounts of energy to response load requirement when FCHEV is accelerating, and have enough capacity to recycle energy during FCHEV braking. The voltage and SOC of ultracapacitor can be calculated through following

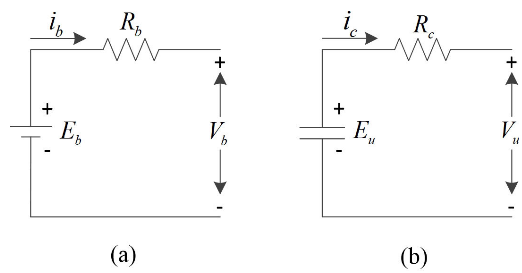


FIGURE 3. (a) Schematic diagram of battery model; (b) Schematic diagram of ultracapacitor model.

equation [35]:

$$V_u(t) = E_u(t) - R_c i_c(t) \tag{7}$$

$$SOC_u(t) = \frac{(E_b(t) - 2R_c i_c(t))^2}{V_{uc,max}^2} \tag{8}$$

where V_b, E_u, i_c, R_c denote terminal voltage, capacitor voltage, load current, equivalent resistance, respectively. SOC_u is the ultracapacitor SOC and $V_{uc,max}$ is ultracapacitor maximum voltage.

III. ENERGY MANAGEMENT STRATEGY OF FCHEV

Considering different characteristics of three energy sources in FCHEV, the diagram of the proposed EMS is shown in Figure 4. Frequency decoupling-based energy management strategy consists of two parts: adaptive low-pass filter design based on fuzzy control and power sharing algorithm based on Harr wavelet transform and fuzzy control, which decomposes required power of FCHEV into three frequency ranges. The low-pass filter is fed with required power and generates the lower frequency component P_{fc_b} that will be assigned to fuel cell and battery, while the difference between P_{req} and P_{fc_b} that will be sent to the ultracapacitor as the higher frequency component. Then, appropriate reference power signals for fuel cell (P_{fc}^{ref}) is obtained through Harr wavelet-based power allocating algorithm. Moreover, one fuzzy controller is designed to determine final power of fuel cell based on battery SOC and efficiency of fuel cell. The two parts of the proposed EMS will be discussed in detail as follows

A. ADAPTIVE LOW-PASS FILTER DESIGN BASED ON FUZZY CONTROL

Low-pass filter can separate effectively the high frequency part of the required power and distribute it to the ultracapacitor in real time, which has advantages in short calculation time and simple design for the practical application in FCHEV. It has been confirmed to be one promising method in designing EMS of FCHEV based on [36]. The transfer function and regulatory factor of the low-pass filter in this paper is chosen as follows:

$$\begin{cases} G(s) = \dfrac{1}{Ts+1} \\ f_s = \dfrac{1}{T} \end{cases} \tag{9}$$

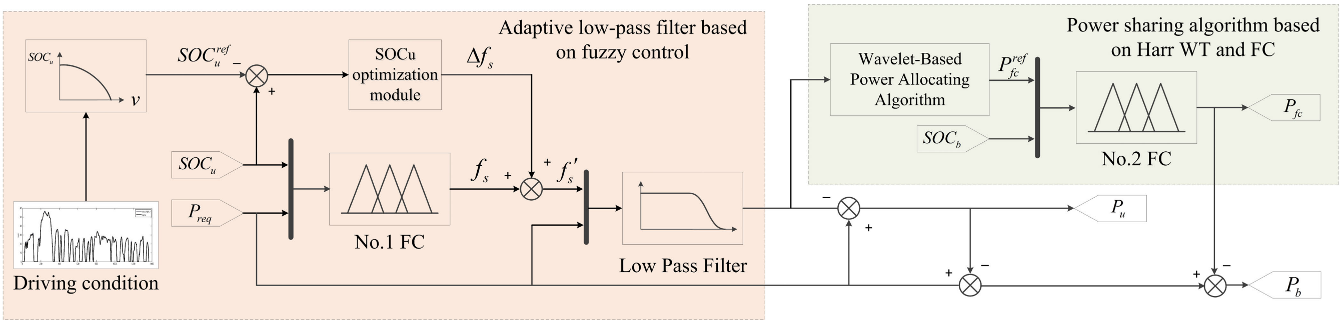


FIGURE 4. **Frequency decoupling-based energy management strategy using fuzzy control method.**

where T is the time constant of the low-pass filter, f_s is the regulating frequency.

As for the low-pass filter, the time constant is adapted to required power and ultracapacitor by the designed fuzzy controller (No.1 FC) automatically. The main purpose of No.1 FC: To maintain ultracapacitor SOC in a given range ($0.4 < SOC_u < 1$), which allows for ultracapacitor to provide/absorb fast peak power effectively when vehicle accelerations or brakes in short-term and relieve pressure on fuel cell and battery by reducing their power fluctuations at the same time. The input variables of the No.1 FC are the ultracapacitor state of charge SOC_u and the required power P_{req}, and output variable is the regulating frequency f_s. Appropriate parameters f_s in different driving conditions is considered based on input-output fuzzy membership functions and fuzzy rule base, respectively, shown in Figure 5 and Table 2.

TABLE 2. **No.1 FC rule base.**

f_s		P_{req}				
		NB	NS	ZE	PS	PB
SOC_u	S	S	S	B	M	RS
	M	RS	RS	B	M	S
	RB	M	M	B	RS	S
	B	B	B	B	RS	S

S: Small, ZE: Zero, M: Medium, B: Big, R: Relatively, N: Negative, P: Positive.

As for No.1 FC, if required power is positive higher (acceleration of vehicle), decreasing f_s to make ultracapacitor provide vast amounts of energy when ultracapacitor SOC is high; if required power is negative higher (deceleration of vehicle), increasing f_s to make ultracapacitor recover large part of regenerative energy when ultracapacitor SOC is low; if required power is lower, only fuel cell and battery can meet the power demand well, ultracapacitor only needs to provide a low level of energy to avoid small power fluctuations on fuel cell and battery; moreover, in order to avoid the over discharging/charging of ultracapacitor, f_s is properly adjusted when ultracapacitor SOC increases or decreases.

Moreover, considering that in actual driving, when FCHEV runs at a low speed, next moment is likely to accelerate, so ultracapacitor should have more energy to prepare for acceleration. Meanwhile, during FCHEV running at a high

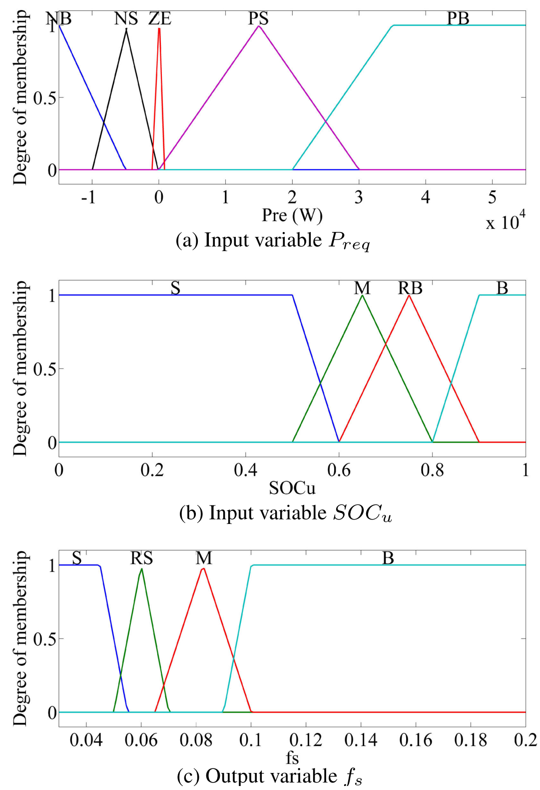


FIGURE 5. **Inputs membership functions and output membership function of No.1 FC.**

speed, there is a greater possibility of braking at next moment, so ultracapacitor should have enough room to recovery braking energy. Ultracapacitor reference SOC (SOC_u^{ref}) related to driving conditions is defined as follows.

$$SOC_u^{ref} = \frac{(v_{max} - v)}{v_{max}} SOC_u^{max} \tag{10}$$

where v_{max} is the max speed of vehicle, SOC_u^{max} is the max ultracapacitor SOC.

In order to guarantee ultracapacitor SOC close to its reference SOC, and change according to driving conditions, an adjusting frequency increment Δf_s is defined to correct the output of No.1 FC, f_s, realizing ultracapacitor to

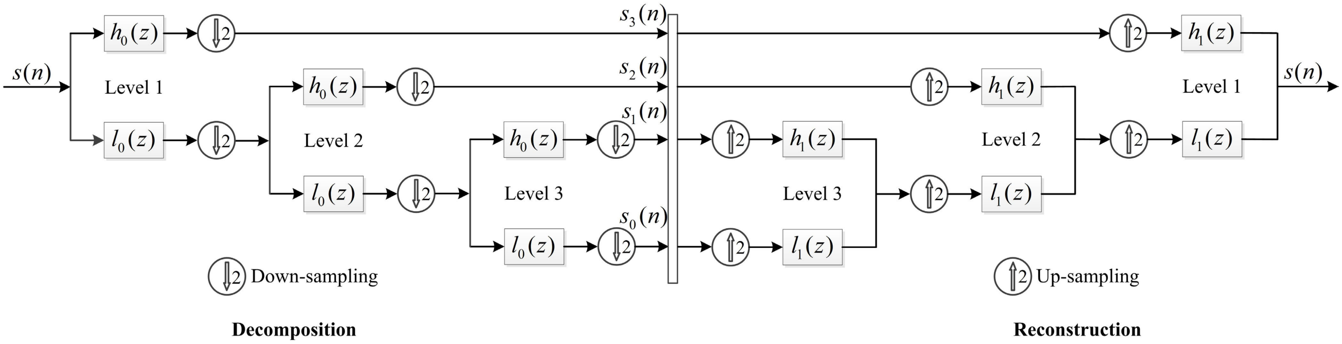


FIGURE 6. Decomposition and reconstruction process of three-level Haar wavelet transform.

change according to driving conditions. The final corrected regulating frequency is expressed as follows:

$$\begin{cases} f_s' = f_s + \Delta f_s \\ \Delta f_s = k(SOC_u - SOC_u^{ref}) \end{cases} \tag{11}$$

where k is regulatory factor.

B. POWER SHARING ALGORITHM BASED ON HARR WAVELET TRANSFORM AND FC

The high frequency component of required power is distributed to ultracapacitor by the adaptive low-pass filter in the above subsection. As for low frequency component, since P_{fc_b} still contains some high frequency components, which can cause power fluctuations on fuel cell and cut its lifespan, it cannot be directly allocated to fuel cell using a simple approach. In this paper, wavelet transform is employed to decouple the high frequency and low frequency components of P_{fc_b}, by utilizing its extract characteristics of the transient signal and sharp changes in the load.

Since the signal of P_{fc_b} is discrete in one dimension, discrete wavelet transform (DWT) and inverse discrete wavelet transform are defined as follows:

$$W(\lambda, u) = \int s(t)\frac{1}{\sqrt{\lambda}}\Psi(\frac{t-u}{\lambda})dt, \quad \lambda = 2^j,\ u = k2^j,\ k \in Z \tag{12}$$

$$s(t) = \sum_{j=Z}\sum_{k=Z} W(j,k)\Psi_{(j,k)}(t) \tag{13}$$

where $s(t)$ is original signal, λ is scale parameter, u is position parameter, Ψ is mother wavelet and W is wavelet coefficient.

Motivated by [37], [38], in this paper, the energy distribution process of FCHEV can be regarded as one stationary process in the short time. Considering advantages on the shortest filter length in the time domain of the Haar wavelet, Harr wavelet is chosen as the mother wavelet to reduce difficulties in decomposition calculation for obtaining trade-off between guaranteeing the proposed EMS utilized in real time application and improving the wavelet transform performances. Hence, it is chosen as the mother wavelet, expressed as follows:

$$\Psi(t) = \begin{cases} 1 & 0 \le t \le 0.5 \\ -1 & 0.5 < t \le 1 \\ 0 & otherwise \end{cases} \tag{14}$$

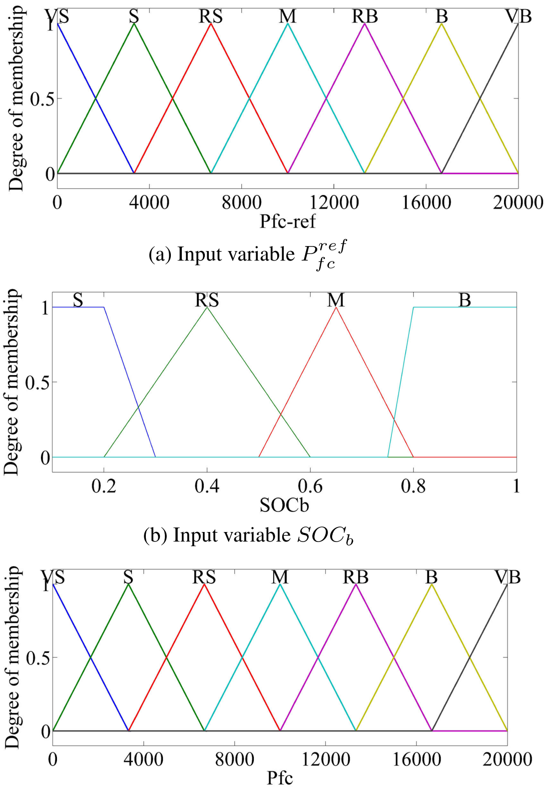
Three-level Haar wavelet decomposition and reconstruction are applied to the original signal $s(n)$ as shown in Figure 6. The original signal $s(n)$ is decomposed into reference signal and detail signal by a low-pass filter $l_0(z)$ and a high-pass filter $h_0(z)$, and the original signal $s(n)$ is reconstructed with very slight errors by reconstruction filter bank $[h_1(z), l_1(z)]^T$. Thus, the low and high frequency components of $P_{fc\_b}^{ref}$ are separated directly. Finally, reference power of fuel cell is obtained as follows:

$$P_{fc}^{ref} = s_0(n) \tag{15}$$

where $s_0(n)$ is the approximation part (reference signal) achieved after the final decomposition.

The low frequency decomposition of P_{fc_b} through DWT provides initial approximation on the fuel cell power references. However, battery SOC is not taken into account. Battery should have enough energy to support fuel cell when vehicle is accelerating, and have enough capacity to recycle energy during braking, which important to fuel economy. In order to make fuel cell operates in high efficiency region and avoid over charging/discharging of battery, other fuzzy controller (No.2 FC) is designed which determines the required power value from fuel cell. The No.2 FC has two input variables and one output variable. The input variables include the fuel cell reference power generated by the Haar wavelet transform, and battery SOC, where output variable is the fuel cell power P_{fc}. For No.2 FC, the block diagram including input and output membership functions is shown in Figure 7, and fuzzy rule base is clarified in Table 3.

The rule base of the developed No.2 FC consists of two parts: fuel cell will produce more power when battery SOC is low and P_{fc}^{ref} is high, vice versa. Main target of No.2 FC is to decrease the fuel consumption by using battery as much as possible whenever it has enough charge and maintaining battery SOC in a proper range.



(a) Input variable P_{fc}^{ref}

(b) Input variable SOC_b

(c) Output variable P_{fc}

FIGURE 7. Inputs membership functions and output membership function of No.2 FC.

TABLE 3. No.2 FC rule base.

P_{fc}		P_{fc}^{ref}						
		VS	S	RS	M	RB	B	VB
SOC_b	S	RS	M	RB	B	VB	VB	VB
	RS	S	RS	M	RB	B	VB	VB
	M	VS	S	RS	M	RB	B	VB
	B	VS	VS	S	RS	M	RB	B

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. SIMULATION RESULTS

To show the efficiency of the proposed EMS, the rule-based EMS using merely fuzzy control [27] and EMS based on ECMS [39] are chosen to be compared by using Advisor/Simulink. In this paper, a model of fuel cell/battery/ultracapacitor hybrid vehicle is developed. The parameters of the power transmission system are clarified in Table 4.

The initial SOC of battery and ultracapacitor are set to 0.7 and 0.9, respectively. As for FCHEV, EMS has an impact on the instantaneous maximum output power of the vehicle. For example, the dynamic response of the fuel cell is slow and it cannot reach its maximum peak power instantaneously. Therefore, it is important for EMS to limit the output of fuel cell for extending its service life. Meanwhile, EMS also needs to adjust the output of battery and ultracapacitor according

TABLE 4. The parameters of power transmission system.

Fuel cell system			
Type	PEM	Max net power(kW)	30
Total mass (kg)	163	Average efficiency (%)	56
Battery			
Type	Lithium-ion	Max capacity (kWh)	9.25
Average efficiency (%)	85	Max power (kW)	20
Ultracapacitor			
Type	Maxwell	Max capacity (Wh)	350
Average efficiency (%)	98	Max power (kW)	70
Motor			
Type	PMSM	Max power (kW)	75
Max torque(N·m)	488	Average efficiency (%)	90
DCDC converter			
Max efficiency(%)	90		

to their SOC to avoid overcharge and over discharge, which will affect the dynamic performance of FCHEV. The results of vehicle dynamic performance test are given in Table 5 first. It can be seen from that, with the proposed EMS, acceleration time for 0-100 km/h of the vehicle is reduced to 8.4 seconds and achieves 36.84% and 10.64% improvement compared to the fuzzy control and ECMS. In addition, other acceleration test parameters are generally better than fuzzy control and ECMS, which shows that EMS proposed in this paper has achieved good dynamic performance of the vehicle.

Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS) and New European Drive Cycle (NEDC) drive cycle are the typical road conditions representing highway, city and suburbs, respectively. Thus, they are selected to analyze the performance of EMS proposed. Vehicle speed and power profiles are present in Figure 8. Then, the simulation results are given in Figures 9-12.

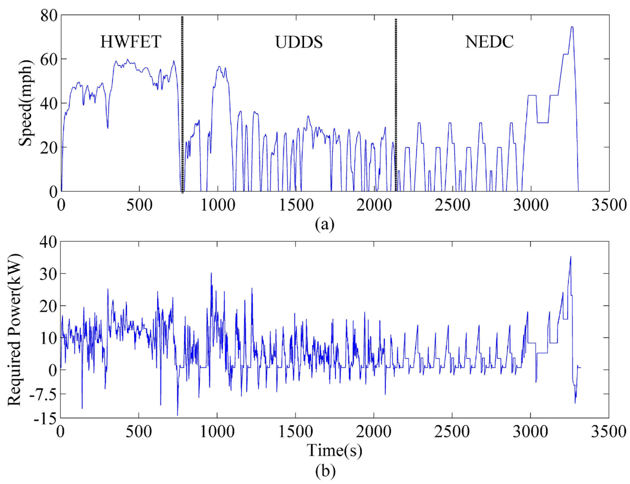


FIGURE 8. Configuration profiles of the HWEFT+UDDS+NEDC road condition.

Figure 9 shows the power distribution of fuel cell, battery and ultracapacitor, it can be seen that ultracapacitor supplies the peak power when FCHEV accelerates, which reduces the impact of load surge on fuel cell/battery and achieves fast response of required power. Fuel cell is satisfied with a base portion of the required power without facing to transient

TABLE 5. The results of vehicle dynamic performance test.

Parameter	EMS proposed in this paper	Fuzzy control	ECMS
Acceleration time for 0-100km/h (s)	8.4	13.3	9.4
Acceleration time for 64-97km/h (s)	3.9	6.9	5.2
Acceleration time for 0-137km/h (s)	22.3	31.1	26.7
Maximum acceleration rate (m/s^2)	4.94	4.94	4.94
Maximum speed (km/h)	152	150	150
Distance in 5 s (m)	195.2	168.8	174.3

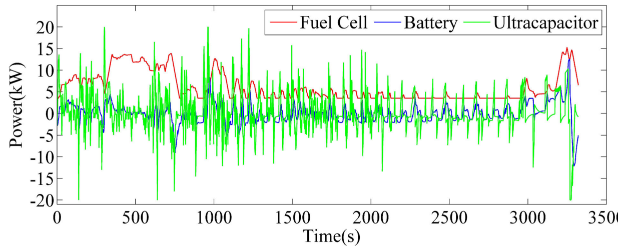


FIGURE 9. The simulation results of EMS proposed in HWFET+UDDS+NEDC road condition.

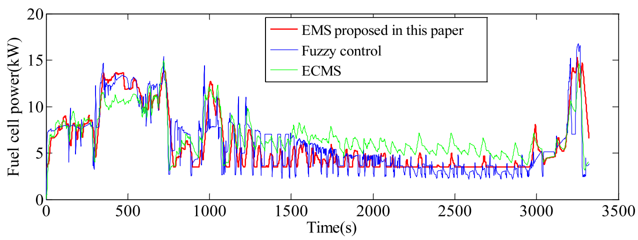


FIGURE 10. Comparison of fuel cell power between three EMSs.

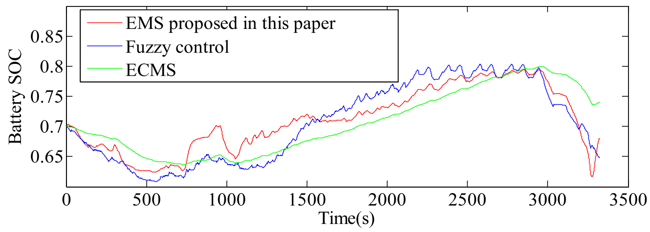


FIGURE 11. Comparison of battery SOC between three EMSs.

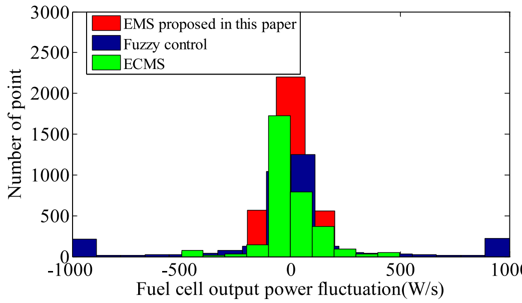


FIGURE 12. Comparison of fuel cell power fluctuation between three EMSs.

changes as the major energy source, which meets most of the load requirements during the operation of the FCHEV. Battery helps fuel cell to supply the steady state power required to further reduce fuel cell power fluctuation. It is noteworthy that fuel cell system almost operates at high efficiency region under the proposed EMS, which can achieve good fuel economy by reducing hydrogen consumption.

Figure 10 shows comparison of fuel cell power between three EMSs, it can be observed by contrasting with Figure 10 that, with the proposed EMS of this paper, the output power of fuel cell is relatively more stable and smoother compared to the fuzzy control and ECMS especially when the vehicle accelerates, further lead to a longer lifetime of the fuel cell.

Figure 11 shows the comparison of battery SOC. According to Figure 11, it can be found that all the EMS can maintain the battery SOC in the optimal zone. But it is also obvious that with the proposed EMS, battery SOC is fluctuating by less than 2%, which can make vehicle run extra distances in case of hydrogen limitation.

In order to show more in detail the advantages of the proposed strategy in reducing power fluctuation of fuel cell, comparison of fuel cell power fluctuation (variation of fuel cell output power per second) [34] is shown in Figure 12. It can be seen from Figure 12 that, with the fuzzy control and ECMS, fuel cell power fluctuations up to ±1000W/s and ±500W/s, respectively, and the EMS proposed in this paper can better suppress fuel cell output power fluctuations in the range of −200W/s to 200W/s, which can effectively improve the fuel cell lifespan.

Furthermore, for a fair comparison of hydrogen consumption under two EMSs, the equivalent hydrogen consumption of battery and ultracapacitor need also to be taken into account. The equivalent hydrogen consumption of the FCHEV is defined as follows:

$$m_{H_2}{}' = \int_0^t \frac{P_{fc}(t)}{\eta_{fc}\rho_{H_2}}dt + \frac{\Delta SOC_b \cdot f_b \cdot 3600}{\eta_{fc}\rho_{H_2}} + \frac{\Delta SOC_u \cdot f_u \cdot 3600}{\eta_{fc}\rho_{H_2}} \tag{16}$$

where $m_{H_2}{}'$ is equivalent hydrogen consumption of the FCHEV, ρ_{H_2} is the hydrogen chemical energy density, f_b and f_u are equivalent factors of battery and ultracapacitor, ΔSOC_b and ΔSOC_u are indexed value of the difference between final and initial SOC_b and SOC_u.

Then the hydrogen consumption comparison of different control strategies is list in Table 6. It can be seen that, the

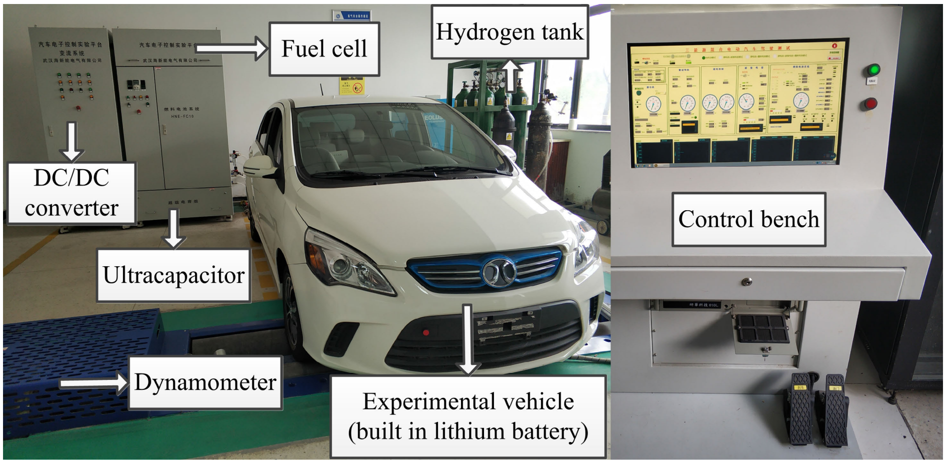


FIGURE 13. Test platform in the lab.

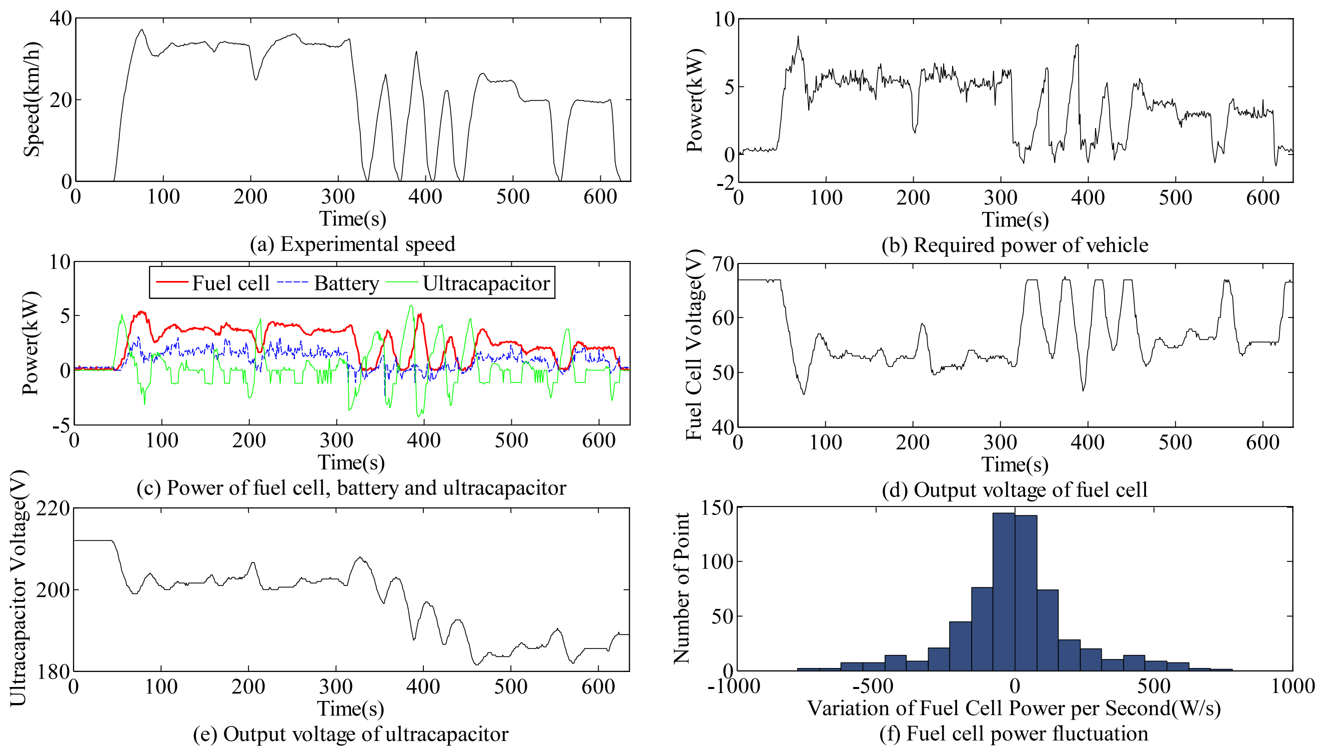


FIGURE 14. Experimental results: (a) Experimental speed, (b) Required power of vehicle, (c) Output power of fuel cell, battery and ultracapacitor, (d) Output voltage of fuel cell, (e) Output voltage of ultacapacitor, (f) Fuel cell power fluctuation.

TABLE 6. Comparison of hydrogen consumption between three EMSs.

Hydrogen consumption(L)		
EMS proposed in this paper	Fuzzy control	ECMS
16.789	17.067	18.237

EMS proposed saves about 1.63% of hydrogen in comparison to the EMS based on fuzzy control under HWFET+UDDS+NEDC driving cycles. Compared with ECMS, the proposed method even can save 7.94% hydrogen consumption. As for the fuel economic improvement in this paper, we focus on the whole performance of FCHEV, including fuel cell lifespan, vehicle power performance and fuel economy. It is very important to guarantee the proposed EMS to realize the trade-off among different objections. And from Figure 10, it is obvious that the fuel cell power fluctuation is restrained greatly at the cost of a little increased hydrogen consumption, especially for acceleration and deceleration of the vehicle. Therefore, the proposed EMS of this paper can achieve higher efficiency of fuel cell system and reduce hydrogen consumption to improve fuel cell economy and whole efficiency of FCHEV.

B. EXPERIMENTAL RESULTS

A test platform in the lab is used to further verify the real-time control performance of the proposed EMS. The presented test platform consists of fuel cell system, ultracapacitor system, experimental vehicle (built in lithium battery), unidirectional DC/DC converter, bidirectional DC/DC converter and control bench as shown in Figure 13. Detail parameters of presented platform are listed in Table 7. Compared with fuel cell parameters in the simulation, the maximum output power of fuel cell in the experimental platform is reduced to 10kW, which is caused by the limitation of the experimental cost. Therefore, in order to protect the fuel cell from overload, the maximum speed of experimental vehicle is limited to 40 km/h. The online driving cycle is generated by controlling accelerator pedal and brake pedal, as shown in Figure 14(a) (b). The initial voltage of ultracapacitor is set to 212V.

TABLE 7. Parameters of platform.

Parameters	Value
Fuel cell rate power (kW)	10
Output voltage range of fuel cell (V)	40-100
Unidirectional DC/DC converter rate power (kW)	10
Battery energy (kWh)	25.6
Ultracapacitor energy(Wh)	320
Output voltage range of ultracapacitor (V)	128-288
Bidirectional DC/DC converter rate power (kW)	10
Motor rate power (kW)	45

Power allocation between three energy sources is shown in Figure 14(c). It can be seen that, ultracapacitor provides vast amounts of energy to handle fast peak power (high-frequency components) when the vehicle accelerates, which allows fuel cell and battery to respond to power demand at a slow rate. Fuel cell supplies average power (low-frequency components) throughout the whole drive cycle to meet the normal driving demands for FCHEV. Battery provides a long-term supplemental power (middle-frequency components) for fuel cell to further reduce the power fluctuation of fuel cell during acceleration of FCHEV. In addition, battery and ultracapacitor absorb braking energy completely during brakes of FCHEV, which is beneficial for improving the fuel economy.

Output voltage of fuel cell is shown in Figure 14(d). It can be seen that, fuel cell voltage decreases with the increase of its output power, the maximum variation of fuel cell voltage obtained by the proposed EMS is limited to 21V, which guarantees fuel cell supply power smoothly. Figure 14(e) shows output voltage of ultracapacitor, where ultracapacitor voltage fluctuates seriously to make ultracapacitor respond to power demand as quickly as possible when the vehicle accelerates. With the efficient utilization of ultracapacitor, the dynamic performance of FCHEV can be guaranteed.

In order to show the power fluctuation of fuel cell more intuitively and further verify the advantages of proposed EMS in extending fuel cell lifespan, fuel cell power fluctuation (variation of fuel cell output power per second) is shown in Figure 14(f). It can be seen from Figure 14(f) that, with the proposed EMS, fuel cell power fluctuation is mainly limited to 200W/s during the most part of a drive cycle. With smooth power output of fuel cell, fuel cell lifespan can be effectively improved.

V. CONCLUSION

In this paper, the frequency decoupling-based EMS for FCHEV using fuzzy control method has been proposed and investigated to extend fuel cell lifetime and improve fuel economy. The proposed EMS allows required power of FCHEV to be decomposed into three components with three frequency ranges based on Harr wavelet transform and an adaptive lower filter using one fuzzy controller. According to the proposed frequency decoupling, the obtained three frequency required power is supplied by fuel cell/battery/ultracapacitor, respectively, in order to achieve a trade-off between fuel economy, power performance and fuel cell durability. The simulation results, compared with the EMS based on fuzzy control and ECMS, shows that fuel cell and battery satisfy a base portion of the required power without facing to transient changes, which is beneficial to extend their lifespan under HWFET+UDDS+NEDC condition. Meanwhile, the EMS proposed saves about 7.94% of hydrogen in comparison to ECMS, which achieves better fuel economy. The proposed EMS can relax computation burden on on-line application on the experimental bench in the lab. From the obtained results of the experimental bench, the proposed EMS can effectively reduce impact of power fluctuations on fuel cell, extend its lifespan and reduce fuel consumption.

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