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A NOVEL WAVELET BASED LOAD SHARING ALGORITHM FOR FUEL CELL AND ULTRA-CAPACITOR BASED HYBRID VEHICULAR POWER SYSTEM

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ABSTRACT
A fuel cell (FC) and ultra-capacitor (UC) based hybrid power system using a well-designed power flow control strategy can result in better energy efficiency and reduced cost of fuel cell power technology. The most critical attribute of a power control strategy for a hybrid electric vehicle (HEV) is the sharing of power demand between available power sources. The load demand profile of HEV is a non-stationary fluctuating signal and consisting of transients. Recently, wavelet transforms have been used for analyzing and evaluating such signals for dynamic systems. This paper focuses on the development of a novel wavelet-based load sharing algorithm for FC/UC hybrid vehicular power system in order to ensure efficient power flow control strategy.

KEY WORDS
Fuel cell, hybrid system, power management, ultra-capacitor, vehicular application, wavelet

1. Introduction

Fuel cell based vehicles have the potential to significantly improve the fuel economy and can be three times more efficient than traditional internal combustion engines [1], [2]. The development of FC infrastructure and associated technologies have been advancing rapidly in order to improve overall system efficiency under realistic automotive loads while meeting the demands under dynamic response related to transient loads or cold start conditions [3].

A stand-alone FC system integrated into an automotive power-train is not always sufficient to satisfy the load demands of a vehicle [4]. Although FC systems exhibit good power capability during steady-state operation, the response of fuel cells during transient and instantaneous peak power demands is relatively poor. Thus the FC system can be hybridized with a UC bank to meet the total power demand of a HEV. The UC bank can assist the FC system to achieve good performance during startup and while acceleration [5]. Optimization of the power flow and control strategies according to the power demand can be used to increase energy efficiency, and reduce the cost and size of fuel cell power technology. Therefore, the total power demand of an HEV can be optimally shared between an FC and a UC by considering the load characteristics.

To share the total load demand between FC and UC according to their natural characteristics, we observed that wavelet transform can provide a very suitable structure in order to develop HEV power flow strategies. Consequently, in this paper, a new wavelet-based load sharing algorithm is developed for FC/UC hybrid vehicular power system.

2. System Description

2.1 Driving Schedule of Hybrid FC/UC Based Vehicular Power System

The UDDS road is selected as a reference cycle to model, design and simulate the proposed HEV power system. Figure 1 shows the speed of the HEV according to standard UDDS driving cycle as a function of time. Specific characteristics of this cycle are shown in Table 1.

Table 1.Specific characteristics of UDDS drive cycle is obtained from ADVISOR

Time	1369 [s]
Distance	7.45 [miles]
Max. speed	56.7 [mph]
Avg. speed	19.6 [mph]
Max. accel.	1.48 [m/s^2]
Max. decel.	-1.48 [m/s^2]
Avg. accel.	0.51 [m/s^2]
Avg. decel.	0.58 [m/s^2]
Idle time	259 [s]

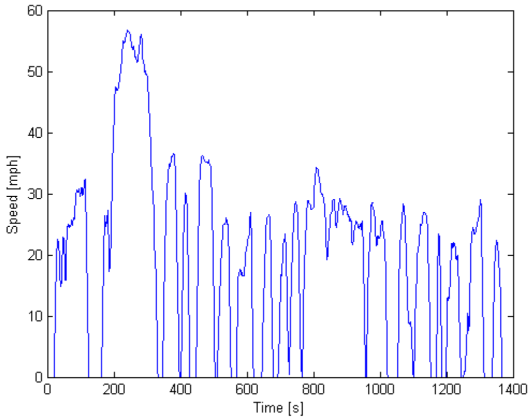

Fig. 1. The variation of vehicle speed according to UDDS driving cycle.

To model the dynamic load characteristics of the FC/UC hybrid vehicle, we utilize the load profile data as shown in Fig. 2 obtained from the Advanced Vehicle Simulator (ADVISOR®) analysis tool simulations according to the urban dynamometer driving schedule (UDDS) road.

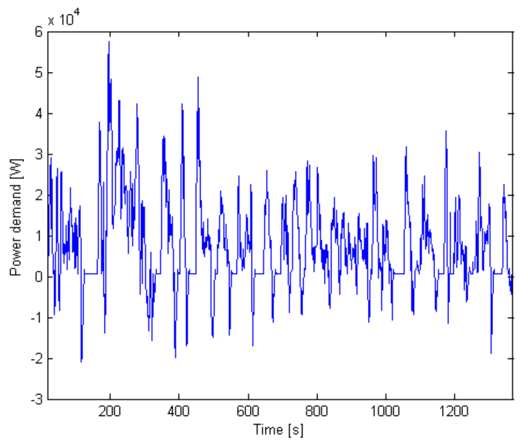

Fig. 2. Power demand according to UDDS driving cycle road for an FC powered vehicle.

This load power profile is a non-stationary signal and consists of transients. The wavelet transform can be effectively used for analyzing power transients in HEV power demand profile, because of its ability to deal with non-stationary and/or transient signals.

2.2 Wavelet Based Load Sharing Algorithm

A given signal can be decomposed into transients and desired characteristics can be extracted simultaneously in both the time and frequency domain by using the wavelet transform (WT). The parameters used in the WT for this study are as follows:

a scale
b position
h_0, l_0 high-pass filter, low-pass filter for decomposition
h_1, l_1 high-pass filter, low-pass filter for reconstruction
j, k discrete time
K_ψ a constant depending on ψ
U discrete location
s original signal
T time
W wavelet coefficients
ψ mother wavelet functions

Continuous Wavelet Transform (CWT) is defined as the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet functions ψ [6], expressed as

$$W(scale, position) = \int_{-\infty}^{\infty} s(t)\psi(scale, position, t)dt\ . \qquad (1)$$

In CWT, wavelet coefficients W are obtained as a function of scale and position [6]. Wavelets are short and sensitive to the local changes in the signal [7]. Thus, the wavelet transform can provide a filter to extract characteristics of non-stationary and/or transient signals and sharp changes [6], [8] in the load profile.

Obtaining the different signal structures such as non-stationary and/or short-time transients is highly depended on the selection of wavelet basis function used for processing the signal. In other words, the selection of wavelet basis plays an important role in detecting and localizing different types of transients [9]. A series expansion of dilated and translated versions of the basis function, which is called the mother wavelet, multiplied by appropriate coefficients supplies the process representation using wavelets [8]. A mother wavelet can be written as [6]

$$W_{a,b}(t) = \int_{\Re} s(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt,\ \ a \in \Re^{+} - \{0\}, b \in \Re\ . \qquad (2)$$

where the dilation or scale parameter "a" controls the length of the frequency band, the position parameter "b" controls the size of the time window. The WT decomposes $s(t)$ into various components at different time intervals and frequency bands as a windowing technique. In wavelet analysis, long windows are used at low frequencies, and short windows are also used at high frequencies [6], [10].

One of the most popular mother wavelets is Haar wavelet for detecting and localizing of transients. The Haar basis has the shortest filter length in the time domain in comparison to other wavelet bases [8]. Because of the above mentioned features, the Haar wavelet transform is the most suitable functions for filtering HEV power demand load profile, which consists of transients corresponding to sharp peak power demand. The transients of the HEV power demand signal is clearly observed from the short-term frequency and component magnitude changes. The Haar wavelet is defined by [8], [11]

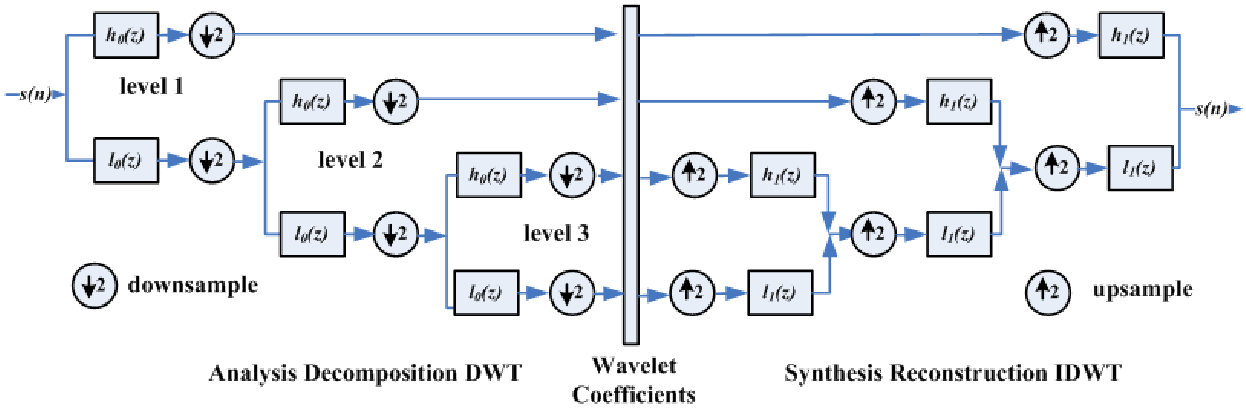

Fig. 3. Decomposition-reconstruction process.

$$\psi(t)=\begin{cases}1, & if\quad 0\le t<\dfrac{1}{2}\\ -1, & if\quad \dfrac{1}{2}\le t<1\\ 0, & otherwise\end{cases}\qquad (3)$$

Compared to CWT, a discrete wavelet transform (DWT) is sufficient to decompose a signal due to the reduction in the number of coefficients as the scaling factor increases [8], [12]. The DWT can be expressed as

$$W_{a,b}(t)=\int_{\Re} s(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt,\qquad (4)$$
$$a=2^j, b=k2^j, (j,k)\in Z^2$$

where the original signal $s(t)$ is decomposed to obtain coefficients $W(a,b)$. The signal $s(t)$ may be reconstructed from the coefficients $W(a,b)$, which is called WT synthesis. The continuous and discrete inverse wavelet transforms are given by [6],

$$s(t)=\frac{1}{K_\psi}\iint_{R^+R} W(a,b)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)\frac{da\ db}{a^2}\qquad (5)$$

and

$$s(t)=\sum_{j\in Z}\sum_{k\in Z} W(j,k)\psi_{j,k}(t),\qquad (6)$$

respectively. As shown in Fig. 4, the WT algorithm uses a low-pass filter and a high-pass filter in the wavelet decomposition and reconstruction structure. This structure consists of a filter bank to decompose the signal into low and high frequency components. In the filter bank, $l_0(z)$ represents the low-pass analysis filter, and $h_0(z)$ represents the high-pass analysis filter. The low-pass and high-pass filters are combined with down-sampling operations, that is, steps that throw away every other sample at each process, reducing the data size by 50% each time [6], [13]. Similarly, the synthesis filter bank consists of the low-pass synthesis filter $l_1(z)$ and the high-pass synthesis filter $h_1(z)$ with up-sampling operations as shown in Fig. 3.

3. Results

The FC system operates with a UC bank connected in parallel with the dc bus. The block diagram of the proposed system is shown in Fig. 4. As mentioned before, dynamic load characteristic for HEV power flow according to the UDDS driving cycle is obtained from ADVISOR which was shown in Fig. 2.

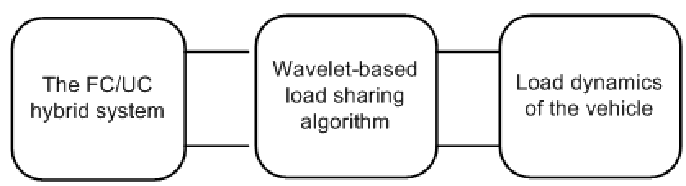

Fig. 4. Block diagram of the proposed system.

The required total power demand of the HEV will be shared between FC system and UC bank. As the wavelet-based load sharing algorithm is applied, smoothed power load profile will be met by the FC system. The remaining high frequency components of load demand which includes transient and abrupt changes of peak power demand will be met by UC. In this algorithm, multi-level Haar wavelet decomposition and reconstruction are applied for the original signal $s(n)$. The signal $s(n)$ is the power demand profile of FC/UC hybrid vehicle. The equivalent filter bank for decomposing and reconstructing the HEV power demand signal in three levels or sub-bands is shown in Fig. 5.

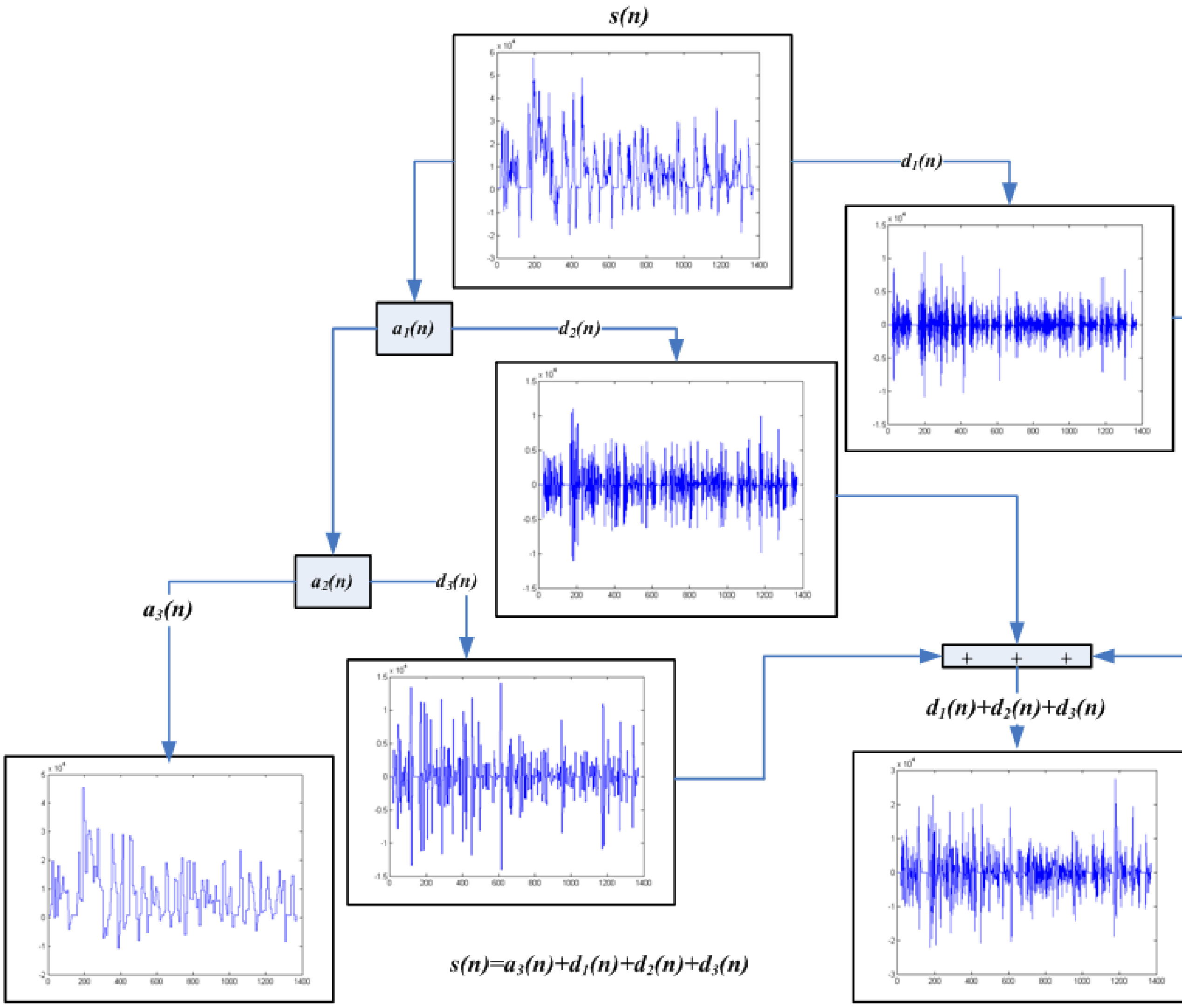

Fig. 5. Reconstructed signal components

After it is reconstructed the original signal from the Haar wavelet decomposition structure, the maximum error is calculated as 2.9104e-011. This error value shows the accuracy and reliability of the sharing algorithm and achieving the perfect reconstruction of the original signal as well.

As shown in Fig. 5, obtaining the signal $a_3(n)$ exhibits the smoothed signal, which can be easily met by the FC system. At the same time, obtaining the sum of the high frequency components ($d_1(n)+ d_2(n)+ d_3(n)$) represents transient signals, which can be satisfied by UC bank. Thus, the power demand signal of the HEV will be satisfied by sharing the load demand between the FC system and UC bank.

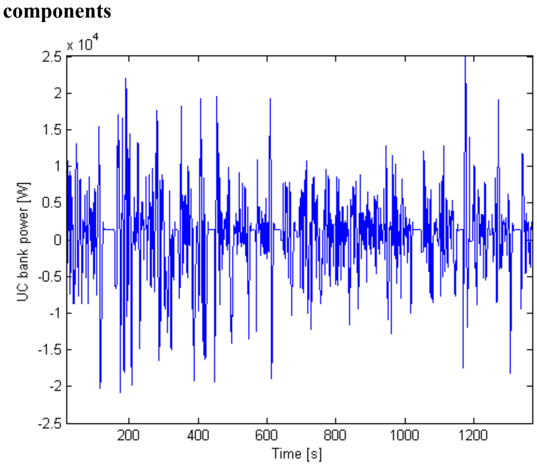

Fig. 6. The variation of UC bank power according to load demand.

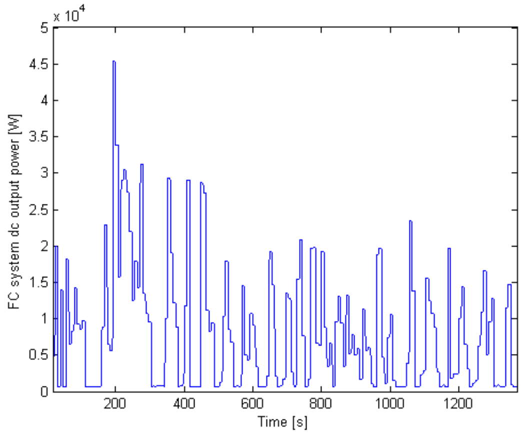

Fig. 7. The variation of FC system dc output power according to load demand.

Figures 6 and 7 are shown the power met by UC bank and FC system, respectively. The UC bank satisfies the transient and peak power load demand while the FC system satisfies the smoothed load demand. From Fig. 8, it is evident that the FC system and UC bank together share this load requirement.

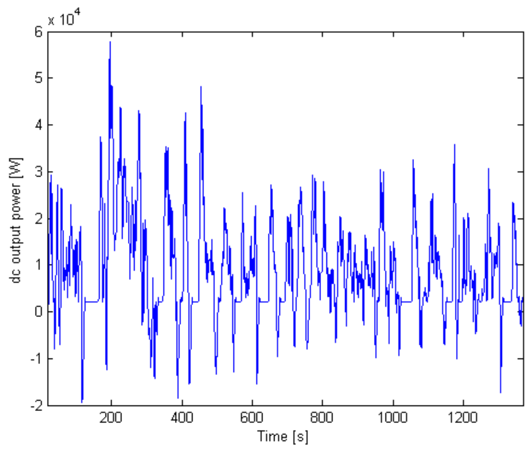

Fig. 8. The variation of FC/UC hybrid system dc output power.

4. Conclusion

The proposed wavelet-based load sharing algorithm exhibits excellent performance for the FC/UC hybrid vehicular applications during the steady-state, transients, and peak power demand periods. Since the load sharing is realized to approximate the natural characteristics of FC and UC, the decomposed loads can be easily and efficiently satisfied. The proposed load sharing algorithm ensures that FC system is not subjected to transients and sharp peak loads. Thus, this system can lead to considerable benefits in terms of vehicle performance, FC system life while reducing the cost of FC power technology and fuel usage.

Acknowledgements

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