Wavelet-transform Algorithm Application in Hybrid Power System Optimization of Electric Vehicles

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Abstract. In order to reduce the changing times of battery’s output power loads and currents, a novel energy management strategy was developed for hybrid power system including a battery pack and an ultracapacitor (UC) pack. The strategy is utilizing wavelet-transform algorithm to allocate power components with different frequency contents among the on-board energy sources. The models of hybrid power system were developed and simulated in MATLAB/Simulink. Simulation results show that: Compared with the logic threshold strategy, the wavelet control method can avoid battery to receive chaotic high-frequency components more effectively. Meantime, the utilization of ultra-capacitor can be improved. Thus battery can be protected and the efficiency of electric vehicles can be increased.

1. Introduction
As energy and environment problems are becoming increasingly serious, electric vehicles (EV) have attracted a great deal of attention over the world because of its great advantage in energy-saving and emission-reduction[1]. Developing energy source is the key technology of EV. At present, battery is the most widely used energy source[2]. With the characteristics of high energy density and low power density, a battery pack would be oversize and overweight in order to satisfy the requirements of both driving distance and dynamic performance simultaneously. Under such instantaneously varying power input and output conditions, batteries perform frequent charging and discharging operations, which tend to have bad effects on the battery life[3]. An Ultracapacitor (UC) has higher power density than a battery[4-6]. Therefore, adding UC to energy storage system can enhance the dynamic performance of EV and reduce the battery’s stress.

Owing to the target that making full use of each energy source, it is necessary to design an energy management strategy to coordinate the power to flow among different energy sources. Thounthong P et al. developed an original energy management scheme that adopts three proportion-integral (PI) algorithms to control three voltage loops. The method can prevent fast changing currents for the fuel cell and battery, which is beneficial to extend the lifetime of energy sources[7]. The fuzzy logic controller was applied to hybrid vehicles. The comprehensive comparisons with the power tracking control strategy verify that the fuzzy controller has better rationality and validity in terms of fuel economy and dynamic property[8]. A model predictive control system (MPC) for a hybrid battery-UC source is put forward. The state of charge of battery and the ultra-capacitor voltage are maintained within predefined limits during the operation of the controller[9]. Ziyou Song et al. utilized a dynamic programming approach to deal with the integrated optimization problem for a hybrid energy system[10]. Meanwhile, they proposed a fuzzy logic controller and a model predictive controller. The fuzzy logic controller achieves the best performance and reduces about 23% of the life cycle cost[11]. Chen Z proposed an intelligent algorithm based on quadratic programming for a series plug-in hybrid electric vehicle, which can decrease fuel consumption[12]. Long B et al. designed an $\mathcal{H}_\infty$ control method which results in good
dynamic response. Under the same conditions, a vehicle can acquire more braking energy than applying a conventional proportion-integral-differential (PID) controller[13]. Pontryagin’s-Minimum-Principle (PMP)-based strategies were developed to control vehicular electric power systems. By means of these strategies, the overall energy consumption and the pollutant emissions can be minimized for a given driving cycle[14].

From the aforementioned previous works, the power management strategies have been proved to be effective in dealing with system power allocation. However, battery cannot avoid completely taking over rapidly changing power loads in real drive conditions. The chaotic high-frequency power loads will result in the degradation of battery, and then do harm to the battery life expectancy [10]. Therefore, avoiding battery from rapid-variation becomes an important subject. Wavelet transform (WT) can be an appropriate solution. Wavelet transform is a new mathematical approach that decomposes an original signal into components at different positions and scales. However, it’s seldom reported that WT is employed as an effective tool for the decomposition of power demands of vehicles.

In this paper, we proposed the wavelet transform method to decompose the needed power into low and high components. The UC provides high peak power requirement, the battery only provides the rest stable power demands. So the battery is not required to provide the fast currents. Moreover, the battery’s life is likely to be extended.

2. System Model

The hybrid power system architecture is shown in Figure 1. It consists of battery DC/DC converter and UC. Figure 2 shows the electrical equivalent circuit used in the battery model development. The nomenclatures of the battery pack are as follows: $V$, battery terminal voltage[V]; $V_{oc}$, battery open circuit voltage[V]; $R_{int}$, internal resistance of the battery[Ω]; $T_{ess}$, battery temperature[°C]; $SOC_{int}$, state of charge of battery pack; $T_{ess\_int}$, battery initial temperature[°C]; $Q_{ess\_gen}$, heat generated by battery[J]; $Q_{ess\_air}$, heat dissipated in the air[J]; $m_{ess}$, battery mass[kg]; $c_{ess}$, specific heat capacity of battery[J/(kg °C)]; $P$, battery output power[W]; $I$, battery current[A]; $Q_{max}$, total capacity[J].

![Figure 1. Hybrid power system configuration](image1)

![Figure 2. Battery electrical equivalent circuit](image2)

In the process of battery charging and discharging, T$_{ess}$ and SOC$_{bat}$ have great influences on R$_{int}$ and V$_{oc}$. So design formulas of R$_{int}$ and V$_{oc}$ can be expressed as

$$R_{int} = f(T_{ess}, SOC_{int})$$  

$$V_{oc} = f(T_{ess}, SOC_{int})$$  

$$T_{ess} = T_{ess\_int} + \int \frac{Q_{ess\_gen} - Q_{ess\_air}}{m_{ess} c_{ess}}$$  

$$V = V_{oc} - IR_{int}$$  

$$P = VI = (V_{oc} - IR_{int})I$$  

$$I = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4R_{int}P}}{2R_{int}}$$
The state-of-charge (SOC) is the percentage of battery surplus capacity and total capacity, which is an important factor for evaluating battery performance. SOC can be expressed as

\[
SOC_{bat} = \frac{Q_{max} - \int_0^t I dt}{Q_{max}}
\]

(7)

Figure 3 shows the electrical equivalent circuit utilized in the UC model development. The circuit parameters are shown as follows: \(i_1\), current flowing into UC[A]; \(i_2\), ideal UC current[A]; \(R_1\), equivalent series resistance[Ω]; \(R_2\), equivalent parallel resistance[Ω]; \(C\), UC capacitance[F]; \(U\), voltage of UC[V]; \(U_{oc}\), UC open-circuit voltage[V]; \(U_{min}\), lower limit of UC voltage[V]; \(U_{max}\), upper limit of UC voltage[V]. \(SOC_{uc}\), state of charge of UC pack.

Figure 3. UC electrical equivalent circuit

In Figure 3, \(R_1\) represents sudden changes of voltage and heat loss in the charging and discharging process. Usually, the value of \(R_1\) is small. \(R_2\) represents self-discharging leakage loss and affects long-term energy storage performance. \(R_2\) only appears when UC has been placed for a long period, so the influence of \(R_2\), is usually neglected. The current and voltage of UC can be written as

\[
i_1 = i_2 + \frac{1}{R_1C} \int_0^t i_2 dt
\]

(8)

\[
U = R_1i_1 + \frac{1}{C} \int_0^t i_2 dt
\]

(9)

The value of \(SOC_{uc}\) is linearly related to the UC open circuit voltage, thus the expression is

\[
SOC_{uc} = \frac{Q_{rem}}{Q_{total}} = \frac{U_{oc} - U_{min}}{U_{max} - U_{min}}
\]

(10)

3. Wavelet Based Energy Management System

Wavelet analysis is a localization tool in both time and frequency domain with a fixed window but a changeable shape, and a changeable time and frequency window. The function of wavelet transform is

\[
WT_t(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi(\frac{t-\tau}{a}) dt
\]

(11)

In Eq. (11), \(a\) is a scale factor, \(\tau\) is a shift factor, \(x(t)\) is the original signal, \(\psi(t)\) is the wavelet function. From Eq. (11) we can see that it is important for the wavelet transform to choose appropriate basic wavelet function that helps \(\psi(t)\) to have short support in the time domain and be more concentrated in the frequency domain, which makes the wavelet transform be capable of comprehending the time and frequency information simultaneously.
Haar wavelet function is a compactly supported orthogonal wavelet function, which is earliest used in the wavelet analysis. The signal approximation results are not ideal owing to the discontinuity of Haar wavelet, so it is not widely used in the signal de-noising aspect. Therefore, it can remove the peak power for the battery by exploiting the discontinuity of Haar wavelet. The Haar function is

$$\psi(t) = \begin{cases} 
1 & 0 \leq t \leq \frac{1}{2} \\
-1 & \frac{1}{2} < t \leq 1 \\
0 & \text{others}
\end{cases} \quad (12)$$

The transform becomes discrete wavelet transform, denoted as DWT [27, 28]. The formula of DWT is expressed as

$$WT_a(x, t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi\left(\frac{t-t'}{a}\right)dt \quad a = 2^j, \tau = k \cdot 2^j, j, k \in \mathbb{Z} \quad (13)$$

Wavelet decomposition process is as follows. The first step is to decompose original signal $x$ into two coefficients, low frequency coefficients $cA_1$ and high frequency coefficients $cD_1$, respectively. Low frequency coefficients $cA_1$ are obtained by convoluting original signal $x$ with low pass filter $Lo_D$. High frequency coefficients $cD_1$ are obtained by convoluting original signal $x$ with high pass filter $Hi_D$. Figure. 4 shows the process of decomposition in the first step.

The next step is to decompose $cA_1$ into $cA_2$ and $cD_2$, and repeat this for every step. Figure. 5 shows one step of the multi-layer wavelets decomposition.

The wavelet decomposition structure of signal $x$ is $[cA_j, cD_j, ..., cD_1]$ in the $j$ layer. Low frequency coefficients $cA_j$ needs to be reconstructed to become low frequency signal $CA_j$ after wavelet decomposition. Then the low frequency signal is passed to the battery pack. The ultra-capacitor receives the rest of original signal.

The decomposition level is up to the signal-to-noise ratio. Signal-to-noise ratio is the ratio of effective signal and noise signal. High signal-to-noise ratio represents less noise in the original signal. In this paper, the power demand of UDDS cycle is assumed as the original signal with high-frequency noise signal. The low frequency signal to battery pack is effective signal, the high frequency signal is considered to noise signal. Here, the practical significance of signal-to-noise ratio is the energy ratio between the battery and UC. There are two important factors to consider in selecting the signal-to-noise ratio. First, the battery pack should be the main energy source. So the value of signal-to-noise ratio is greater than 1; Secondly, for the sake of increasing utilization of UC, the signal-to-noise ratio ought to be as small as possible. Consequently, the value of signal-to-noise ratio is selected to be 2, the corresponding decomposition level is 5. Therefore, the power signal is decomposed into five layers of wavelet coefficients by using Haar wavelet. The low frequency signal $CA_5$ are received by the battery pack, meanwhile, all high frequency coefficients are accepted by the UC pack.
4. Results and Discussions

The simulation results are shown in Figures 6-11 for the battery pack power, UC pack power, SOC of battery pack, SOC of UC pack, battery pack current, and bus voltage, respectively. Figure 6 shows battery power curves. Output power variation per second is called as power changing rate. With the wavelet controller, the maximum absolute value of the charging power is 189W. The time of zero power changing rates is 1277 seconds. The battery pack will supply the UC pack with power when the output power of battery pack is greater than bus power demand. With the logic threshold controller, the maximum absolute value of the charging power is 2263W. The time of zero power changing rates is 248 seconds. The logic threshold controller is 11 times higher in power changing number than the wavelet controller. As a result, the battery power controlled by wavelet is relatively stable.

From Figure 7, the UC group controlled by the wavelet transform has been working in 1369 seconds because it provides the transient power to EV. According to the statistics analysis, the discharging energy of UC group controlled by the wavelet transform is 2572kJ. And the charging energy is 2463kJ. When the logic threshold controller is used, the UC group participates to work only when the bus power demand is greater than average power. The work time is 653 seconds. The energy which the UC pack provides is 2086kJ. Meanwhile, the charging energy is 716kJ. Consequently, the UC pack controlled by logic threshold rules takes over fewer power loads. Figures 6 and 7 show that the bus power is successfully decomposed into low frequency and high frequency components by wavelet transform.
The variation of battery pack SOC is shown in Figure 8, the initial value of battery SOC is set to 0.7. Both of two strategies can maintain SOC around the initial value. The final value of SOC controlled by logic threshold is a little greater than that controlled by wavelet. However, the difference is small, just 0.005. The battery controlled by wavelet absorbs less recovery regenerative braking energy and supplies power to the UC pack on occasion. Therefore, the final value controlled by wavelet is smaller. The initial value of UC SOC is set to 0.8. From Fig. 9, the SOC for UC pack controlled by wavelet fluctuates in a small range from 0.79 to 0.81, which ensures enough energy to accelerate and enough space to store regenerative energy.

The reason of stable SOC is that the UC receives regenerative energy and the power which the battery pack provides simultaneously. The SOC of UC pack controlled by logic threshold decreases fast and the final value is be close to 0.7. The UC energy is only supplemented by regenerative braking energy after long term discharging. Regenerative braking energy is limited, which cannot guarantee adequate energy in the UC pack.

The current variation is indicated in Figure 10. Output current variation per second is called as current changing rate. The time of zero current changing rates is 1331s. The average value of current changing rates is 0.3A/s, and the charging time is 32s. With the logic threshold controller, the time of zero current changing rates is 733s. And the charging time is 74s. The average current changing rate is 2.2A/s, which is about 7 times that of the average value controlled by the wavelet transform. Thus it’s obvious that wavelet control can defend the battery from accepting transient currents.

The variation of bus voltage is shown in Figure 11. Output voltage variation per second is called as voltage changing rate. The wavelet controller can stabilize the bus voltage in a small range from 316.8V to 320.4V. With the small fluctuation in the voltage, the average voltage changing rate is 0.02V/s. But the variation range of bus voltage controlled by logic threshold is from 316.5V to 321.5V. The value of 0.13V/s is the average voltage changing rate, which is 5 times larger than the value of 0.02V/s. The stability of the bus voltage has great effects on the vehicle efficiency. The bus voltage controlled by wavelet is more stable, thus the vehicle efficiency may be higher.

5. Conclusions
An energy management strategy based on wavelet transform is discussed for a hybrid battery-ultracapacitor vehicular system. The simulation results show that the wavelet method can better stabilize the UC SOC and bus voltage. By using the wavelet transform, the UC pack supplies the transient currents, which protects the battery. Probably, the lifetime of the battery pack can be prolonged.

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7. References
[1] R. Wegmann, V. Döge, D.U. Sauer, Assessing the potential of a hybrid battery system to reduce battery aging in an electric vehicle by studying the cycle life of a graphite NCA high energy and a LTO metal oxide high power battery cell considering realistic test profiles, Applied Energy 226(C) (2018), pp 197-212.
[2] Y. Wang, C. Liu, R. Pan, Z. Chen, Modeling and state-of-charge prediction of lithium-ion battery and ultracapacitor hybrids with a co-estimator, Energy 121 (2017), pp 739-750.
[3] Z. Song, J. Li, X. Han, L. Xu, L. Lu, M. Ouyang, H. Hofmann, Multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles, Applied Energy 135 (2014), pp 212-224.
[4] A. Burke, Ultracapacitor technologies and application in hybrid and electric vehicles, International Journal of Energy Research 34(2) (2010), pp 133-151.
[5] DOUCETTE, T. Reed, MCCULLOCH, D. Malcolm, A comparison of high-speed flywheels, batteries, and ultracapacitors on the bases of cost and fuel economy as the energy storage system
in a fuel cell based hybrid electric vehicle, Journal of Power Sources 196(3) (2011), pp 1163-1170.

[6] X. Rui, Y. Duan, J. Cao, Q. Yu, Battery and ultracapacitor in-the-loop approach to validate a real-time power management method for an all-climate electric vehicle, Applied Energy 217(1) (2018), pp 153-165.

[7] P. Thounthong, S. Raël, B. Davat, Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications, Journal of Power Sources 193(1) (2009), pp 376-385.

[8] L.I. Qi, W. Chen, L.I. Yankun, S. Liu, J. Huang, Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic, International Journal of Electrical Power & Energy Systems 43(1) (2012), pp 514-525.

[9] B. Hredzak, V.G. Agelidis, M. Jang, A Model Predictive Control System for a Hybrid Battery-Ultracapacitor Power Source, IEEE Transactions on Power Electronics 29(3) (2014), pp 1469-1479.

[10] Z. Song, H. Hofmann, J. Li, X. Han, M. Ouyang, Optimization for a hybrid energy storage system in electric vehicles using dynamic programing approach, Applied Energy 139 (2015), pp 151-162.

[11] Z. Song, H. Hofmann, J. Li, J. Hou, X. Han, M. Ouyang, Energy management strategies comparison for electric vehicles with hybrid energy storage system, Applied Energy 134 (2014), pp 321-331.

[12] Z. Chen, B. Xia, C. You, C.C. Mi, A novel energy management method for series plug-in hybrid electric vehicles, Applied Energy 145 (2015), pp 172-179.

[13] B. Long, S. Lim, Z. Bai, J. Ryu, K. Chong, Energy Management and Control of Electric Vehicles, Using Hybrid Power Source in Regenerative Braking Operation, Energies 7(7) (2014), pp 4300-4315.

[14] A.T. Nguyen, J. Lauber, M. Dambrine, Optimal control based algorithms for energy management of automotive power systems with battery/supercapacitor storage devices, Energy Conversion and Management 87 (2014), pp 410-420.