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The Energy Management and Optimization Strategy for Fuel Cell Hybrid Ships

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Abstract—**With the environment pollution being serious, the fuel cell hybrid system is attracting more and more attention. Compared with single energy system, the hybrid power sources enhance the complexity of the system, thus a proper energy management strategy is necessary for keeping the system safe and reliable. Based on the analysis of the fuel cell and ultra-capacitor hybrid system, the wavelet-transform and rule based energy management strategy is proposed and verified by establishing the hybrid system model and simulation in Matlab/Simulink. The result shows that the proposed strategy can lever the characteristics of the different power sources and keep the state of charge of the ultra-capacitor in normal level.**

Keywords-ship energy management; fuel cell; hybrid power system; wavelet transform

I. INTRODUCTION

With the rising concern of the environment problem, the application of renewable energies is widely studied, especially in ship industry. The fuel cell has been one of the most promising technologies for its high efficiency and energy density as well as zero emission [1]. Compared with the solar and wind energy, fuel cell system is less influenced by the weather condition and in compare with the traditional internal combustion engine, fuel cell system produces less emission and no noise pollution. There are many types of fuel cells according to the different electrolytes in which the proton exchange membrane fuel cell (PEMFC) is preferred in this paper for its relative high energy density, light weight and simple construction [2-3].

However, although there are many advantages, the wide application of fuel cell is still limited due to its poor dynamic performance, inability of energy storage and the safety of the hydrogen. Therefore, fuel cells are often adopted as the main power sources of electric vessels while various types of energy storage devices are used to store energy and satisfy the peak power requirement. Thus the fuel cell hybrid power system (FCHPS) is adopted. On the other hand, shipboard electric propulsion systems experience large power and torque fluctuations on their drive shaft due to propeller rotational motions and waves [4], so the ultra-capacitor (UC) is selected as the energy storage system (ESS) because of its relative high power density and excellent dynamic characteristics.

In order to coordinate the different dynamic characteristics of the hybrid power system, various energy management strategies (EMSs) have been studied. Yupeng Yuan et al [5] proposed a logic threshold based energy management strategy for a diesel engine and fuel cell hybrid ship. The result shows that the system efficiency can be improved. Similarly, an energy management strategy based on the operating states is introduced in [6]. An agent based energy management strategy was developed in [7]. Philip Stone et al [8] and Hyeongjun Park et al [9] developed the model prediction control to minimize the cost function and F. D. Kanellos et al [10] developed the dynamic programming algorithm subjected to ship operation and environmental and travel constraints to solve the problem for all-electric ships.

However, those EMSs put their emphasis on the whole system but fail to take into account the dynamic characteristics of respective power generation units. In this paper, the wavelet method is proposed to decouple the power demand into high and low frequency. The decoupled power demand is split to different power sources according to their characteristics. The rest of this paper is organized as follows: On Section II, the hybrid power system is modeled. Section III introduces the proposed EMS, and the simulation result is presented and analyzed on Section IV. Finally, the concluding remarks of the work is presented on Section V.

II. MODELING THE SYSTEM

The proposed hybrid system is shown in Fig. 1. The fuel cell is connected to the directed current (DC) bus through a boost DC/DC convertor while the UC supplies and draws energy from the common bus through a buck-boost DC/DC convertor. The fuel cell supplies the basic load while the UC deals with the pulse load. When the required power of the ship is larger than the basic load, the UC is put into action immediately to share the demand load. On the other hand, when the ship requires less load, the UC can be recharged by the fuel cell. The required power of both the propulsion load and the service load is satisfied from the common bus, which also increases the complexity of the system.

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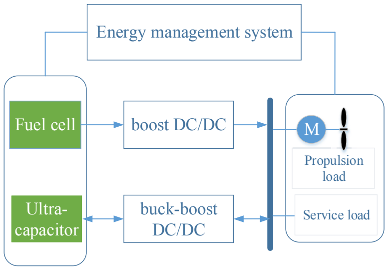


Figure 1. The fuel cell hybrid system.

A. Modeling the Fuel Cell System

In this paper, the fuel cell system is model as the proposed method in [11] as it has been showed to well present the fuel cell system behavior with relatively low error rate.

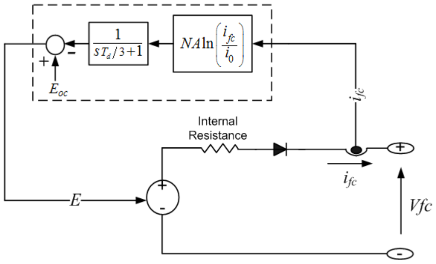


Figure 2. The PEMFC equivalent circuit.

The model is based on the equivalent circuit in Fig. 2 and can be found in SimPowerSystems in Matlab/Simulink. The thermodynamic voltage generated from the electro-chemical reactions is given by the Nernst equation as follows:

$$E_n = 1.229 + (T-298)\times\frac{-44.43}{2F} + \frac{RT}{2F}\ln\left(P_{H_2}P_{O_2}^{1/2}\right) \quad (1)$$

The output voltage of the fuel cell is given by the following equation

$$V_{\mathrm{fc}} = E_n - V_{act} - V_{ohmic} \quad (2)$$

where E_n is the stack output voltage, V_{act} is the activation overvoltage, and V_{ohmic} is the ohmic overvoltage.

The voltage of N series cells is:

$$V_{fc} = N\cdot V \quad (3)$$

where N is the number of cells.

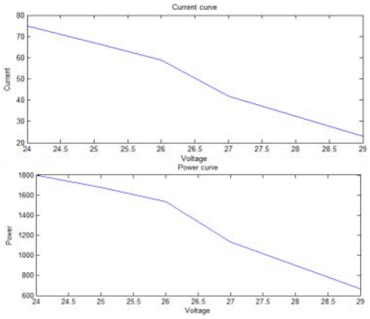


Figure 3. The characteristics of the given PEMFC.

The characteristics of the fuel cell used in the ship are given in the above figure. The maximum power of the fuel cell is 1800W while the voltage is 26V. And the current is 60A.

B. Modeling the Ultra-capicitor

UC is an electrochemical capacitor used to provide peak power for short durations. It is qualified as high power densities as well as unlimited number of charging and discharging times compared to battery and it is robust and maintenance free [12]. The model in [13] is adopted here as shown in Fig.4.

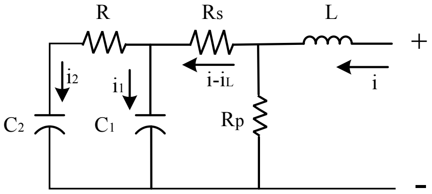


Figure 4. The UC equivalent circuit.

In the proposed circuit, the RC circuit consisting of R_s and C_1 is used to simulate the fast response of a super capacitor and therefore called the fast response branch. The RC circuit formed by R and C_2 is a slow response branch for simulating the internal energy distribution at the end of charging or discharging. The series inductance L usually takes a smaller value, which can be used for fast changing load requirements. The resistance R_p is the equivalent parallel resistance to model self-discharging.

The output voltage of the UC is expressed as:

$$V_{UC} = V_{C_1} - V_{R_S} - V_L \quad (4)$$

where the voltage of *Rs* can be calculated as:

$$V_{R_S} = R_S(i - i_L) \quad (5)$$

The voltage of L is:

$$V_L = L\frac{d_i}{d_t} \quad (6)$$

The voltage of capacitor C_1 and C_2 can be expressed respectively as:

$$V_{C_1} = V_C^O - C_1^{-1}\cdot\int i_1 dt \quad (7)$$

$$V_{C_2} = V_C^O - C_2^{-1}\bullet\int i_2 dt \quad (8)$$

And the current of i_L, i_1 and i_2 can be calculated respectively by:

$$i_L = V_{R_p}/R_P \quad (9)$$

$$i_1 = i - i_L - i_2 \quad (10)$$

$$i_2 = \left(V_{C_1} - V_{C_2}\right)/R \quad (11)$$

The energy of the UC is:

$$E = \frac{1}{2}C\cdot V_{UC}^2 \quad (12)$$

And the maximum energy can be calculated as:

$$E_{\max} = \frac{1}{2} C \cdot V_{\max}^{2} \tag{13}$$

The SOC is an important parameter of UC and can be calculated as [14]:

$$SOC = E \cdot E_{\max}{}^{-1} \tag{14}$$

C. Modeling the DC/DC Convertors

The fuel cell system and UC are connected to the common DC bus through a boost DC/DC convertor and a buck-boost convertor respectively. The UC supplies energy or draws power from the bus under the control of the proposed EMS.

The model of the boost convertor is shown in Fig. 5.

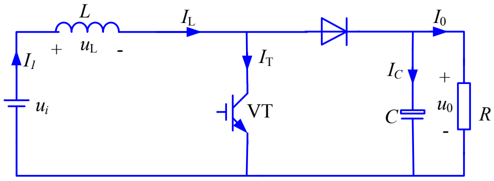


Figure 5. The model of boost convertor.

For the boost DC/DC converter, assuming the values of L and C are large enough, when VT is on, the inductor L and the load R are charged by U_i and the capacitor C respectively. During the period when VT is on, which is expressed as t_{on}, the energy stored in L can be expressed as:

$$E_{on} = EI_L t_{on} \tag{15}$$

Conversely, during VT is off, which is expressed as t_{off}, the energy released by L can be expressed as:

$$E_{off} = (U_o - U_i) I_1 t_{off} \tag{16}$$

In a cycle, E_{on} should be equal to E_{off}, so we can get:

$$U_o = T \cdot t^{-1}_{off} \cdot U_i = \alpha U_i \tag{17}$$

where α is called duty cycle and α>1.So by changing the value of α,the output voltage will be increased.

The model of the buck-boost convertor is represented in Fig. 6.

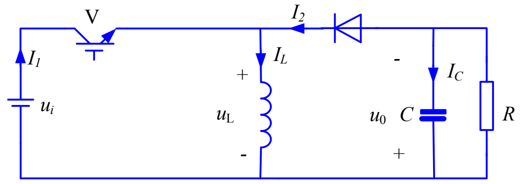


Figure 6. The model of buck-boost convertor.

Similarly, the output voltage of the buck-boost can be expressed as:

$$U_o = \frac{t_{on}}{t_{off}} U_i = \frac{t_{on}}{T\text{-}t_{on}} U_i = \frac{1\text{-}\alpha}{\alpha} U_i \tag{18}$$

Therefore, when 0< α<1/2, the convertor performs as a buck convertor while 1/2< α<1, the convertor performs as a boost convertor.

III. THE ENERGY MANAGEMENT STRATEGY

Most of the present energy management strategies are based on rules, which neglects the dynamic performance of the power sources. When the load change rapidly, there will be harmful effect on the fuel cell, even permanent damage [15]. Furthermore, the EMS needs to consider the state of charge (SOC) of the ESS to keep the system work constantly.

The wavelet transform decomposes an original signal into components at different positions and scales. It can be used to extract signal information in both time and frequency domains and has been successfully applied to many signal processing problems. So it is adopted in this paper to decouple the power requirement.

The different wavelet transform (DWT) is defined as:

$$DWT_{j,k} = \int_R x(t)\overline{\psi_{j,k}(t)}dt = 2^{-\frac{j}{2}} \int_R x(t)\overline{\psi\left(2^{-j} \bullet t - k\right)}d(t) \tag{19}$$

The Haar wavelet basis has the shortest filter length in the time domain in comparison to other wavelet bases [16], so it is chosen as the mother wavelet here. The Haar wavelet is defined by:

$$\psi(t) = \begin{cases} 1 & t \in \left[0, \frac{1}{2}\right) \\ -1 & t \in \left[\frac{1}{2}, 1\right) \\ 0 & otherwise \end{cases} \tag{20}$$

And it is shown in Fig. 7.

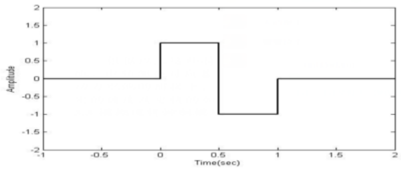


Figure 7. The Harr wavelet.

The high transient power is designed to be supplied by UC and the base power is supplied by PEMFC. In order to achieve the goal, a three level Haar wavelet decomposition and reconstruction are used, which can be seen in Fig. 8. The initial signal *x(n)* is decomposed by a high-pass filter *H_1(z)* and low-pass filter *H_0(z)* into the detail signal and the approximate signal.

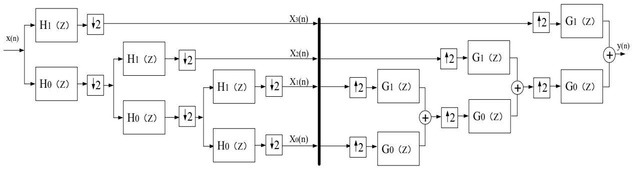


Figure 8. Three level wavelet decomposition and reconstruction diagram.

The total detailed power signal can be inferred as:

$$P_{detail} = X_1(n) + X_2(n) + X_3(n) \tag{21}$$

And the approximate power signal is:

$$P_{app} = X_0(n) \tag{22}$$

Considering the rated power of the fuel cell is 1500W, the reference power of fuel cell is:

$$P_{ref\_fc}=\begin{cases}P_{app}, & P_{app}\le 1500W\\ 1500, & P_{app}>1500W\end{cases}\tag{23}$$

The detailed power is supplied by the UC, so the reference power can be calculated by:

$$P_{ref\_uc}=\begin{cases}P_{detail}, & P_{app}\le 1500W\\ P_{detail}+P_{app}-1500, & P_{app}>1500W\end{cases}\tag{24}$$

The wavelet transform doesn't take SOC of the UC, so some basic rules must be made to prevent over-charge or over-discharge. The rules are as follows:

- If SOC<40% and the ship required power <1500W, all the power demand will be supplied by fuel cell, and UC will be charged by the fuel cell. In this case, the power of the fuel cell and UC is:

$$P_{fc}=1500W\tag{25}$$

$$P_{uc}=P_{requirement}-1500W\tag{26}$$

- If SOC>90%, the UC is regarded at very high SOC, so it needn't to be charged. If its reference power got from the wavelet transform is negative, then the real power output should be zero:

$$P_{fc}=\begin{cases}P_{ref\_fc} & P_{ref\_uc}\ge 0\\ P_{ref\_fc}+P_{ref\_uc} & P_{ref\_uc}<0\end{cases}\tag{27}$$

$$P_{uc}=\begin{cases}P_{ref\_uc} & P_{ref\_uc}\ge 0\\ 0 & P_{ref\_uc}<0\end{cases}\tag{28}$$

- In other cases, the real power outputs of fuel cell and UC equal to the reference power.

$$P_{fc}=P_{ref\_fc}\tag{29}$$

$$P_{uc}=P_{ref\_uc}\tag{30}$$

IV. SIMULATION AND ANALYSIS

The ship power requirement and the reference power are shown in the Fig. 9.

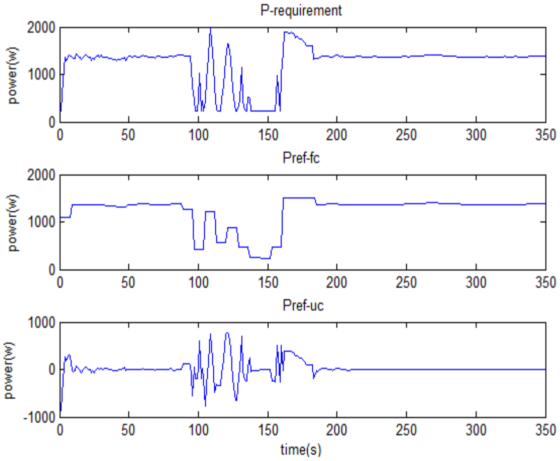
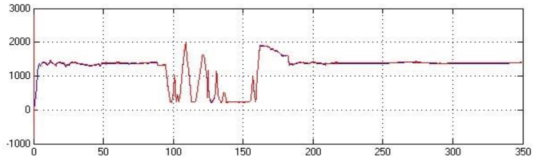


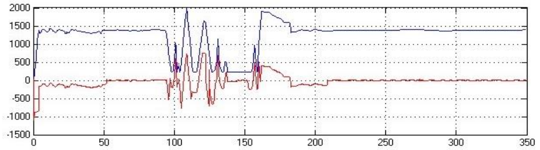
Figure 9. Power requirement and reference power.

The power requirement curve includes several typical operation conditions: cruising (0~90s and 180~350s), docking (90~130s), stop (130~160s) and sailing (160~180s). It can be seen from the figure that the output of fuel cell is steady while the UC supplies the power demand with high frequency.

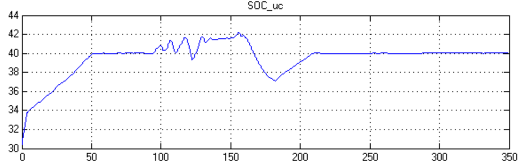
Based on the different initial SOCs of the UC, two cases are simulated. When the initial SOC of the UC is 30%, the result is shown in Fig.10. The blue curve represents the power requirement and the red lines represent the output of fuel cell and UC. The variation curve of SOC is shown in (c).



(a) Power requirement and fuel cell system output power.



(b) Power requirement and ultra-capacitor output power.

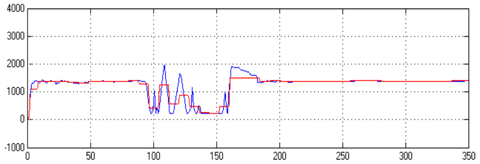


(c) SOC of the ultra-capacitor.

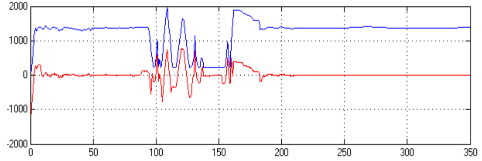
Figure 10. The simulation results in case1.

It can be drawn from the figure that the fuel cell supplies the smooth part of the power requirement while the UC shares the rapidly changing part. In the beginning, the output power of the fuel cell is larger than the ship required power and the SOC of UC is at very low level. Therefore, the fuel cell recharges the UC while satisfying the power requirement. When t=50s, the fuel cell stops charging the UC and after charging and recharging, the SOC of UC keeps stable at 40%.

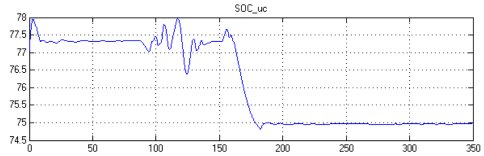
When the initial SOC of the UC is 80%, the result is shown in Fig. 11.



(a) Power requirement and fuel cell system output power.



(b) Power requirement and ultra-capacitor output power.



(c) SOC of the ultra-capacitor.

Figure 11. The simulation results in case2.

The result shows that when the initial SOC is at high level, the UC will discharge and the SOC will also be maintained at reasonable range. Based on the result of the simulation, we can see that the wavelet-transform and the rules can split the power requirement reasonably and maintain the SOC in a normal level. Thus the hybrid system can work safely and reliably.

V. CONCLUSION

Aiming at the fuel cell and ultra-capacitor ship hybrid ships, the wavelet transform is adopted to optimize the output of power sources. The ship required power is decoupled into high and low frequency, and split to fuel cell and ultra-capacitor according to their dynamic performance. The proposed EMS prolongs the service life of fuel cell and improve the reliability of the system. The proposed methods can also be applied to other fuel cell hybrid systems suffering from high- frequency transient power.

The present EMS can be used in small passenger ships. When it comes to large ships in complex sea condition, the proposed EMS is still too simple. In further study, the EMS should be improved to deal with the uncertainty in ship's sailing in the sea.

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REFERENCES

[1] Y. Zhan, Y. Guo, J. Zhu, and L. Li, Power and energy management of grid/PEMFC/battery/supercapacitor hybrid power sources for UPS applications, In International Journal of Electrical Power & Energy Systems, Vol, 67. 2015, pp. 598-612.

[2] P. Thounthong, S. Raël and B. Davat. Energy management of fuel cell /battery / super capacitor hybrid power source for vehicle applications. In Journal of Power Sources, Vol. 193, 2009, pp.376-385.

[3] Yun Wang, Ken S. Chen, Jeffrey Mishler, S. C. Cho and X. C. Adroher, A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research, In Applied Energy, Vol. 88, 2011, pp. 981-1007, ISSN 0306-2619.

[4] V. Salehi, B. Mirafzal and O. Mohammed, "Pulse-load effects on ship power system stability," IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society, Glendale, AZ, 2010, pp. 3353-3358. doi: 10.1109/IECON.2010.5675297.

[5] Y.Yuan, K.Wang and X. Yan. Design and simulate of snergy management control strategy for hybrid ship. Ship & ocean engineering, vol. 44, 2015, pp.95-98.

[6] J. Han; J. Charpentier and T. Tang. An Energy Management System of a Fuel Cell/Battery Hybrid Boa. Energies, vol. 7, 2014, pp. 2799-2820.

[7] D. Tang, X. Yan, Y. Yuan, K. Wang and L. Qiu, "Multi-agent Based Power and Energy Management System for Hybrid Ships," 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, 2015, pp. 383-387. doi: 10.1109/ICRERA.2015.7418441

[8] P. Stone, D. F. Opila and H. Park. Shipboard Power Management Using Constrained Nonlinear Model Predictive Control 2015 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, 2015, pp. 1-7.doi: 10.1109/ESTS.2015.7157853

[9] H. Park, J. Sun, S. Pekarek, P. Stone, D .Opila, R. Meyer, et al. Real-Time Model Predictive Control for Shipboard Power Management Using the IPA-SQP Approach. in IEEE Transactions on Control Systems Technology, vol. 23, no. 6, pp. 2129-2143, Nov. 2015. doi: 10.1109/TCST.2015.2402233

[10] F. D. Kanellos, G. J. Tsekouras and N. D. Hatziargyriou, "Optimal Demand-Side Management and Power Generation Scheduling in an All-Electric Ship," in IEEE Transactions on Sustainable Energy, vol. 5, no. 4, pp. 1166-1175, Oct. 2014. doi: 10.1109/TSTE.2014.2336973.

[11] Souleman Njoya Motapon. Design and simulation of a fuel cell hybrid emergency power system for a more electric aircraft: evaluation of energy management schemes. Montreal, Ecole de Technologie Superieure, 2013.

[12] H. Aouzellag, K. Ghedamsi and D. Aouzellag. Energy management and fault tolerant control strategies for fuel cell/ultra-capacitor hybrid electric vehicles to enhance autonomy, efficiency and life time of the fuel cell system. International Journal of hydrogen Energy, vol. 40, 2015, pp.7204-7213.

[13] O. Erdinc, B. Vural, M. Uzunoglu and Y. Ates. Modeling and analysis of an FC/UC hybrid vehicular power system using a wavelet-fuzzy logic based load sharing and control algorithm, in International journal of hydrogen energy, vol.34, 2009, pp.5223–5233.

[14] W. Lin and C. Zheng. Energy management of a fuel cell/ultra-capacitor hybrid power system using an adaptive optimal-control method. Journal of Power Sources, vol. 196, 2011, pp. 3280–3289.

[15] Z. Liu, L. Yang, Z. Mao, W. Zhuge, Y Zhang, L.Wang, et al. Behavior of PEMFC in starvation. In Journal of Power Sources, vol.157, 2006, pp.166–176.

[16] M. Uzunoglu and M. S. Alam, "Modeling and Analysis of an FC/UC Hybrid Vehicular Power System Using a Novel-Wavelet-Based Load Sharing Algorithm," in IEEE Transactions on Energy Conversion, vol. 23, no. 1, pp. 263-272, March 2008. doi: 10.1109/TEC.2007.908366