ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

Electric Propulsion System of Composite Energy Storage System Based on Model Predictive Control

Yu Zhou[1, a], Diju Gao[1], Yao Jiang[1] and Honglei Wei[1]

[1]School of Shanghai Maritime University, Shanghai 201306, China.

[a]877281493@qq.com

Abstract

In order to improve the efficiency of the electric propulsion system, this paper considers the loss of the composite energy storage system, the fluctuation of lithium battery discharge power rate and the state of charge of the supercapacitor, and proposes the model predictive control strategy. Compared with the fuzzy logic control strategy, the current of the lithium battery under the model predictive control strategy is relatively smooth, the loss of the composite energy storage system is relatively reduced by 16.31%, and the efficiency is increased by 4.91%.Simulation results show that the proposed control strategy can effectively reduce the loss of composite energy storage system.

Keywords

Electric propulsion, Energy storage system, Model predictive control.

1. Introduction

Due to a series of problems such as energy crisis and environmental pollution caused by traditional ships, new energy technology has been rapidly developed and widely used in ships. Especially, the electric propulsion ship with energy storage system can reduce the environmental pollution effectively and meet the increasingly stringent environmental protection requirements [1]. As an energy storage component, lithium battery has the advantages of high energy density and zero emission, so it has become the main energy source of electric propulsion ship instead of diesel generator [2]. However, it is difficult for lithium battery to take into account the instantaneous fluctuation of load and the continuous and stable electricity demand. As a power type energy storage element, super capacitor has the characteristics of high power density and fast response speed. The energy storage system composed of battery is equipped on the ship, so that the energy storage system has the high energy density of lithium battery and the high power density of super capacitor at the same time, so as to realize the optimization of different energy storage elements Potential complementary, to meet the needs of the ship's various loads.

The control strategy of the energy storage device is the key technology of the composite energy storage electric propulsion system. The main purpose is to meet the power demand, effectively reduce the energy consumption of the system, improve the efficiency of the electric propulsion system, and ensure the reliable and safe operation of the composite energy storage system. Among the energy control strategies of the energy storage system, the most commonly used methods are as follows: the required power of the load and the remaining capacity of the energy storage are considered, and the rule-based power distribution strategy is adopted to effectively improve the fuel economy of the propulsion system on the premise of satisfying the power performance[3]. The logic threshold control strategy of composite energy storage system is designed to avoid the impact of large current and improve the service life of the battery[4]. In order to solve the problem that the battery bears too much power in the compound energy storage system, the fuzzy control is used to realize the power

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

distribution and reduce the battery current[5-7]. The rule-based control strategy depends on the designer's experience to a great extent. It can't adapt to the complex load conditions very well, and it is difficult to achieve the optimal control. Although the fuzzy control strategy is easy to implement and can adapt to many working conditions, the fuzzy rules tend to be complex when there are many inputs [8], which brings difficulties to the rule making. In recent years, the control strategy based on optimization theory is widely used in composite energy storage control technology. A nonlinear control strategy of energy storage is proposed, which uses super capacitor to compensate the battery power and optimize the discharge current of the battery[9]. Aiming at the oil electric hybrid system, the paper [10-11] puts forward the model predictive control strategy to optimize the power distribution of diesel generator set and power battery set, improve the fuel economy of hybrid ship, but does not consider reducing the system energy consumption.

To solve the problem of insufficient endurance mileage due to the limitation of energy storage capacity, this paper improves the efficiency of electric propulsion system on the premise of meeting the demand of ship power, considers the loss of composite energy storage system, the fluctuation of discharge power of lithium battery and the state of charge of supercapacitor, and puts forward the model predictive control (MPC) strategy, which is combined with fuzzy logic Compared with the control strategy, the MPC control strategy is proved to be effective in reducing system energy consumption and smoothing lithium battery power.

2. Electric propulsion ship with ESS

2.1 The Structure of Proposed System

The energy storage system of electric propulsion ship is composed of lithium battery and super capacitor, which mainly consists of the following topological structures: lithium battery and super capacitor are directly connected in parallel; super capacitor connects Bidirectional DC-DC converter and lithium battery in parallel; lithium battery and super capacitor connect a Bidirectional DC-DC converter respectively and then parallel [4]. In order to distribute power more flexibly and stably, two sets of bi-directional DC-DC converters are used in this system to directly control the lithium battery and super capacitor. The system structure is shown in Figure 1, in which the controller makes reasonable and effective power distribution according to the required power and the state of charge (SOC) of lithium battery and super capacitor.

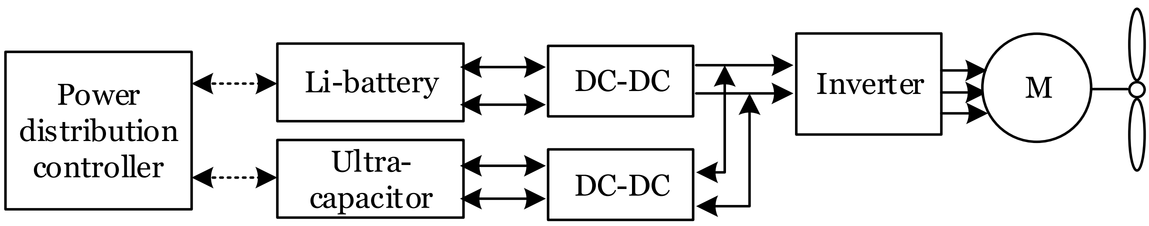

Figure 1. Electric propulsion system structure

2.2 Energy Storage Model

Lithium battery is electrochemical energy storage. It can transform chemical energy and electric energy through its own charging and discharging process. Because of its high storage energy density, lithium battery is the main power source of electric propulsion ship. In order to represent the working characteristics of lithium battery, Thevenin equivalent model is used to reflect the relationship between external voltage and current and internal resistance of lithium battery [12], as shown in Figure 2. According to Kirchhoff's voltage law, the relationship between the equivalent circuit variables of lithium battery is as follows:

$$U(t) = U_b - U_0(t) - R_b i_b(t) \tag{1}$$

Where U_b is the open circuit voltage of lithium battery, $U(t)$ is the terminal voltage, R_b is the internal resistance. The relationship between SOC change and current is as follows:

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

$$\dot{SOC}_b = -\frac{I_b}{Q_b} \tag{2}$$

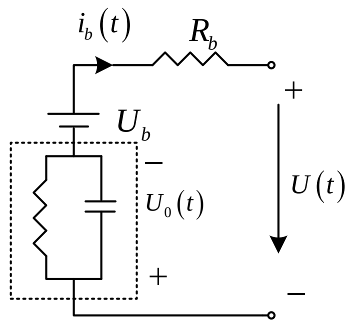

Figure 2. Thevenin model of battery

Where Q_b (Ah) is the total capacity of lithium battery. Thevenin model considers the relationship between electromotive force and SOC, which reflects the dynamic and static characteristics of lithium battery comprehensively, and can accurately simulate the charging and discharging process of lithium battery. Ignoring the terminal voltage of RC parallel circuit, the dynamic response model of lithium battery is established:

$$\dot{SOC}_b = -\frac{U_b - \sqrt{U_b^2 - 4R_bP_b}}{2R_bQ_b} \tag{3}$$

$$P_b = U_b I_b + R_b I_B^2 \tag{4}$$

The ultracapacitor adopts the supercapacitor module BOMD0165 of Maxwell company, also known as double electric layer capacitor. Due to the complex structure of super capacitor, it is difficult to describe its dynamic characteristics. Generally, a specific model is selected according to different applications. According to the load characteristics of electric propulsion ships, the first-order RC equivalent model is adopted as shown in Figure 3. The resistance R_{uc} simulates the ohmic impedance, and the equivalent capacitance C_{uc} represents the storage energy of the super capacitor, which is used to simulate the dynamic process of charge and discharge of the super capacitor [13]. The variables in the first-order RC equivalent model of supercapacitor are as follows:

$$U_c(t) = R_{uc} i_{uc}(t) + \frac{1}{C_{uc}} \int i_{uc}(t)\,dt \tag{5}$$

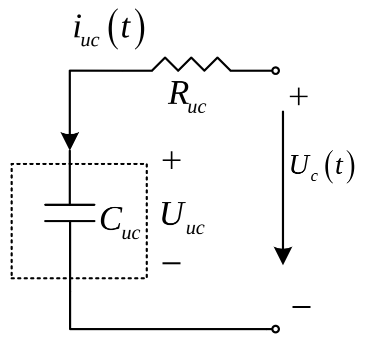

Figure 3. RC equivalent model of ultracapacitor

Assuming that the rated voltage U_{uc} and the internal resistance R_{uc} of the supercapacitor are constant, the SOC of the supercapacitor is represented by the terminal voltage and rated voltage:

$$SOC_{uc} = \frac{U_c}{U_{uc}} \tag{6}$$

There the dynamic response model of supercapacitor is

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

$$\dot{SOC}_{uc}=-\frac{SOC_{uc}U_{uc}-\sqrt{\left(SOC_{uc}U_{uc}\right)^{2}-4R_{uc}P_{uc}}}{2R_{uc}C_{uc}U_{uc}} \tag{7}$$

$$P_{uc}=U_{uc}SOC_{uc}I_{uc}+R_{c}I_{uc}^{2} \tag{8}$$

In the dynamic response model of lithium battery and supercapacitor, P_b and P_{uc} are the power of lithium battery and supercapacitor respectively. The sum of the two meets the demand power, i.e $P_d=P_b+P_{uc}$. Accordingly, a positive power indicates discharge and a negative power indicates charging. The total loss of the energy storage system is:

$$\begin{aligned}P_{total,loss}&=P_{b,loss}+P_{uc,loss}\\&=R_bI_b^2+R_{uc}I_{uc}^2\end{aligned} \tag{9}$$

Where $P_{b,loss}$ and $P_{uc,loss}$ are the power losses of lithium battery and super capacitor respectively.

The specific parameters of lithium battery and super capacitor are shown in Table 1.

Table 1. Parameters of ESS

Description	Parameter	Value
Open-circuit voltage of battery modules	U_b	500V
Capacity of battery modules	Q_b	100Ah
Resistance of one battery	R_b	25mΩ
Rated voltage of one ultracapacitor	U_{uc}	48V
Capacity of one ultracapacitor	C_{uc}	165F
Resistance of oneultracapacitor	R_{uc}	6.3mΩ
Number of batteries	N_b	42
Number of ultracapacitor	N_{uc}	100

3. Control Strategy of Energy Storage System

The electric propulsion system has the characteristics of nonlinearity, time-varying and uncertainty [16]. The core of the control strategy of the energy storage system is to use the super capacitor as the auxiliary energy of the lithium battery, and use the super capacitor to charge and discharge quickly to protect the over-current of the lithium battery, so as to reduce the loss of the energy storage system. Model predictive control is a new type of control algorithm, which is suitable for uncertain, nonlinear dynamic systems. According to the control objectives, different evaluation functions are formulated to achieve accurate and effective control. Therefore, this paper proposes an energy control strategy based on MPC according to the characteristics of composite energy storage electric propulsion ships.

3.1 MPC Problem Formulation

In this paper, the energy efficiency of the electric propulsion system is the main optimization objective to reduce the total power loss of the energy storage system as much as possible. On this basis, in order to delay the service life of the lithium battery, the battery current fluctuation constraint is added, and the stability of the battery current has a direct effect on reducing the system loss [18], and it can realize that the battery bears low-frequency power, and the supercapacitor is the auxiliary energy of the electric propulsion system. During the operation of the system, try to keep the SOC of the supercapacitor more than half of the constraint range, so as to exceed The capacitor can respond to the unknown power demand quickly. The objective function is represented by

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

$$
\begin{aligned}
J=\sum_{i=1}^{N_p}\Big[&P_{total,loss}\left(k+i\,|\,k\right)+\lambda_1\left(\Delta I_b\left(k+i\,|\,k\right)\right)\\
&+\lambda_2\left(SOC_{uc}\left(k+i\,|\,k\right)-SOC_{uc,ref}\right)\Big]
\end{aligned}
\tag{10}
$$

Where N_p represents the prediction time domain; $(k+i|k)$ represents the ith prediction value of the current time k, λ_1 and λ_2 are weight coefficients. For balancing the current of lithium battery and the SOC term of super capacitor, set the weight coefficients to 0.5, respectively. $SOC_{uc,ref}$ as the reference value of super capacitor SOC is setted to 0.7. The weight of different parts of the objective function can be adjusted by changing the weight coefficient. Because there are different dimensions of Multi-Objective in objective function, it is necessary to normalize the objective function (*), and to convert equation (11) into quadratic programming for convenient calculation as

$$
\begin{aligned}
J=\sum_{i=1}^{N_p}\Big[&\left(P^*_{total,loss}(k+i\,|\,k)\right)^2+\lambda_1\left(\Delta I_b^*\left(k+i\,|\,k\right)\right)^2\\
&+\lambda_2\left(SOC_{uc}\left(k+i\,|\,k\right)-SOC_{uc,ref}\right)^2\Big]
\end{aligned}
\tag{11}
$$

$$
P^*_{total,loss}=\frac{P_{total,loss}}{P_d}
\tag{12}
$$

$$
\Delta I_b^*=\frac{I_b\left(k+1\right)-I_b\left(k\right)}{I_b\left(k\right)}
\tag{13}
$$

According to the discrete dynamic model of energy storage system and the above control requirements, SOC of lithium battery and supercapacitor are taken as state variables; current of lithium battery and supercapacitor are chosen as control variables. In order to avoid overcharge and overdischarge of lithium battery and super capacitor, the current and SOC of lithium battery and super capacitor are restricted as

$$
\begin{cases}
0\le I_b\le 2C\\
0.2\le SOC_b\le 0.9\\
-100A\le I_{uc}\le 100A\\
0.3\le SOC_{uc}\le 0.9
\end{cases}
\tag{14}
$$

As the main power supply equipment, lithium battery is not charged in the process of ship operation, and the maximum discharge current of lithium battery is 2C (charge discharge ratio); as an auxiliary energy, super capacitor can absorb and emit power, and cooperate with lithium battery to meet the load power demand.

3.2 Solution of MPC Problem

In the process of solving the optimization problem (11)-(14), the SOC of lithium battery and super capacitor is taken as the state variable; the current of lithium battery and super capacitor is chosen as the control variable, and the optimization objective of model predictive control is established as

$$
\min_{u(k):N_c}\quad J\left(x\left(k\right),u\left(k\right),P_d\left(k\right),N_p\right)
\tag{15}
$$

$$
\begin{cases}
x(k+1)=Ax\left(k\right)+Bu\left(k\right)\\
y\left(k+1\right)=Cx\left(k\right)
\end{cases}
\tag{16}
$$

$$
C\left(x\left(k\right),u\left(k\right)\right)\le 0
\tag{17}
$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

Where $x=\left[SOC_b, SOC_{uc}\right]$, $x(k)$ represents the current state of time k, and the input variable is $u=\left[I_b, I_{uc}\right]$, T_s is the sampling time of the system,(=1s), N_c is the control time domain; $C\left(x(k), u(k)\right)$ is the inequality constraint (14). The coefficient matrixs of the system of state equations as

$$A=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, B=\begin{bmatrix}\dfrac{T_s}{3600Q_B} & 0\\ 0 & \dfrac{T_s}{V_{uc}C_{uc}}\end{bmatrix}, C=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}.$$

For the above nonlinear constrained optimization problems, the sequential quadratic programming (SQP) is used to solve the equations (15) - (17). In each iteration, the search direction is obtained by solving a subproblem of quadratic programming and the next improved iteration point is obtained until the end of the algorithm.

4. Control Strategy of Energy Storage System

In this paper, the hardware in the loop simulation analysis is carried out on the electric propulsion system test platform, which uses the way of propulsion motor and electric dynamometer to simulate the power demand of electric propulsion ship, and its demand power curve is shown in Figure 4. Because the internal resistance of the super capacitor is far less than that of the lithium battery, the system loss can be effectively reduced by making the super capacitor bear more required power. Therefore, an energy control strategy based on MPC is proposed. The prediction time domain used in MPC simulation is 5s, and the control time domain is 1s.

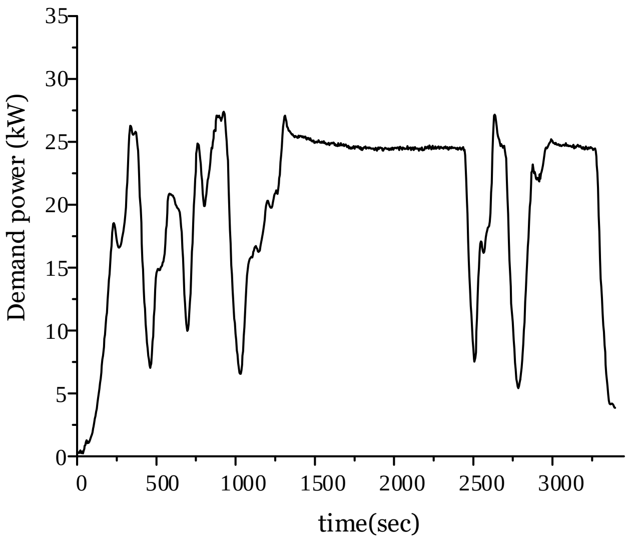

Figure 4. Demand power curve

In order to verify the strategy proposed in this paper, the fuzzy control strategy is taken as a comparison scheme, and the Mamdani fuzzy controller with three inputs and one output is considered. The input parameters are the required power of lithium battery, super capacitor and electric propulsion ship, and the output parameters are the power distribution factor of lithium battery [17]. The power calculation of lithium battery and super capacitor are as follows:

$$P_b = K_{bat} \times P_d \tag{18}$$

$$P_{uc} = \left(1-K_{bat}\right) \times P_d \tag{19}$$

Where the power allocation factor K_{bat} of lithium battery is determined by fuzzy rules. The comparison results of the two control strategies are shown in Figure 5.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

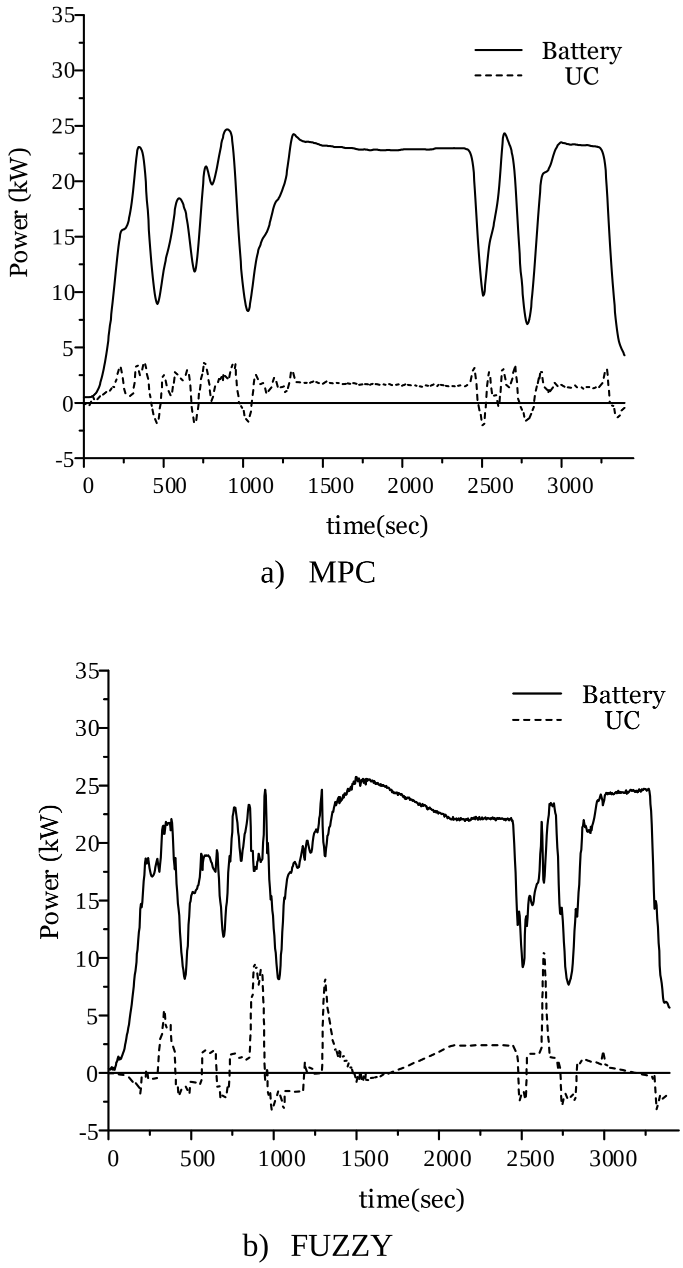

Figure 5. Simulation results of control strategies: a) MPC. b) FUZZY.

As the main power source, the power of lithium battery is always greater than zero; the charging power of super capacitor is provided by lithium battery, and super capacitor is used as auxiliary energy. When the demand power is high, it shares part of the power for lithium battery, effectively reducing the discharge current of lithium battery. MPC introduces a current constraint term into the objective function (11) to suppress the power fluctuation of lithium battery and make the super capacitor bear the high-frequency power. From figure 5 a), it can be seen that the output power of lithium battery under MPC control strategy is smoother than that under fuzzy control strategy, which reduces the bearing power of lithium battery to a certain extent. For the fuzzy control strategy, with the decrease of supercapacitor SOC, its output power is limited by the fuzzy rules. At 1450s, the lithium battery needs to provide high charging power, which makes the system loss increase. In order to evaluate the optimized results of the battery current, the root mean square (RMS) of the battery current is taken as the evaluation index, and the calculation is as follows:

$$RMS = \sqrt{\frac{1}{T_f}\sum_{i=1}^{T_f} I_B^2} \tag{20}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

Where T_f is the simulation time, the loss of battery power is related to the RMS of battery current. When the RMS value is larger, the loss is larger, and the lower the RMS value is, the loss is smaller. Therefore, this value can also be used as the efficiency index of the system. According to the above formula, calculate the RMS value of battery current provided by lithium battery, MPC and fuzzy control. The simulation results are shown in Figure 6. When all the load power is supplied by lithium battery, the RMS of battery current is 42.42A, and the RMS of battery current of energy storage system under MPC and fuzzy control are 39.60A and 41.04A respectively. Compared with the fuzzy control, the MPC strategy proposed in this paper reduces the RMS of battery current by 1.44A, effectively reducing the power of lithium battery.

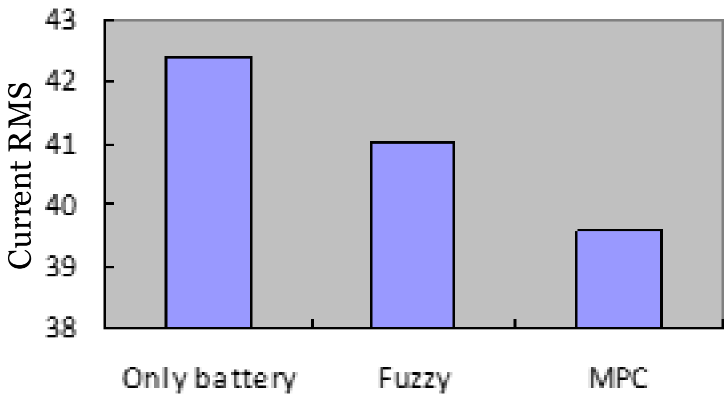

Figure 6. Battery current RMSs

During the simulation operation, SOC of lithium battery and super capacitor is shown in Figure 7. SOC of lithium battery under MPC strategy is 5% higher than that under fuzzy control strategy. From the perspective of sustainability of energy storage system, model predictive control strategy makes composite energy storage system have better endurance. In Figure 8, the SOC of super capacitor is 0.68 under MPC control and 0.726 under fuzzy control. The residual SOC of super capacitor under MPC strategy is lower than that under fuzzy control. It can be seen that MPC makes super capacitor bear more demand power, which can better reduce system loss while ensuring super capacitor is in high charge state.

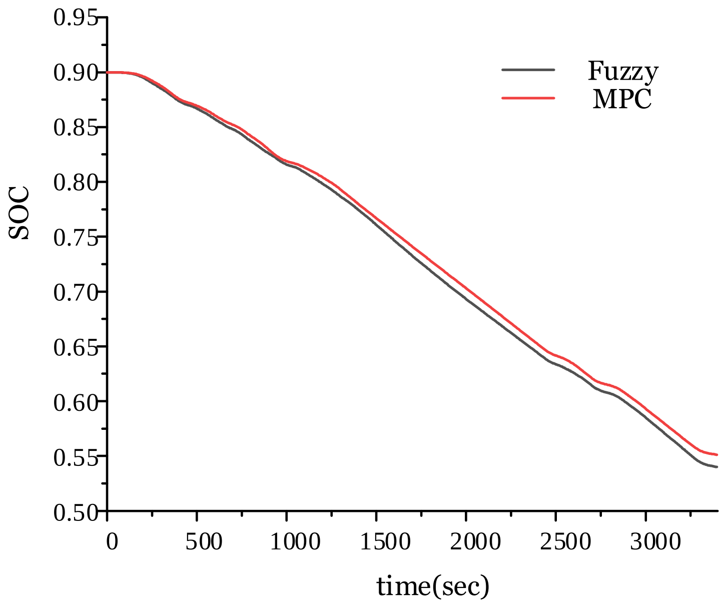

Figure 7. SOC of battery

ISSN: 2414-1895 DOI: 10.6919/ICJE.202005_6(5).0032

In order to quantitatively analyze the control effect of the two strategies, the energy loss of the system is calculated respectively under the same initial value of SOC. According to equation (9), the energy loss of the energy storage system under the control strategy designed in this paper is 10.57kw.h , which is 2.06kw.h less than the energy loss of the fuzzy control strategy. According to the total energy of the simulation time and the energy loss of the energy storage system, the fuzzy control and the Under the proposed control strategy, the system energy efficiency is 65.38% and 70.29%, respectively. See Table 2 for energy storage system energy efficiency results.

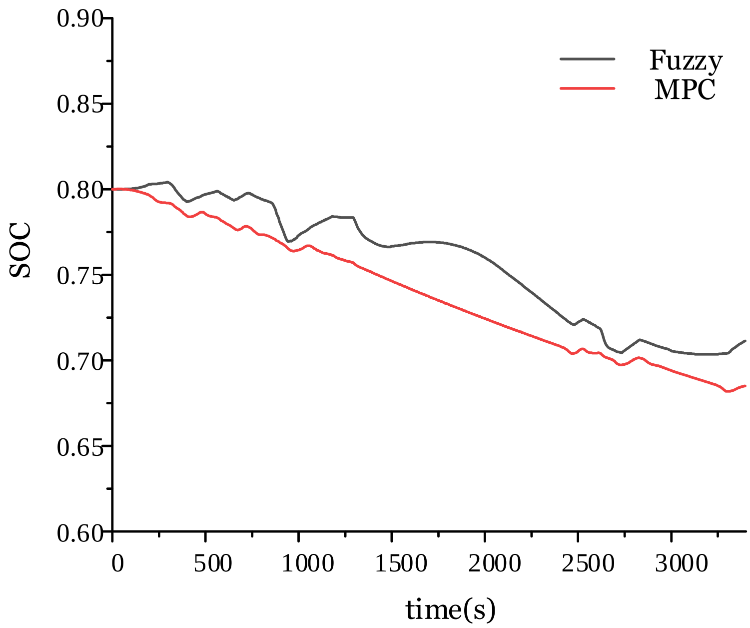

Figure 8. SOC of ultracapacitor

Table 2. Energy efficiency of ESS

Descripe	Energy loss	Energy efficiency
Fuzzy	12.63kW.h	65.36%
MPC	10.57kW.h	70.29%

5. Conclusion

In this paper, the electric propulsion ship with energy storage system is taken as the research object. In order to improve the efficiency of the system, the navigation data of the electric propulsion ship is obtained by using the experimental platform. The MPC control strategy is proposed with the main control objective of minimum energy loss and smooth output power of lithium battery in the composite energy storage system. The simulation results show that compared with the fuzzy control strategy, MPC control strategy can smooth the output power of lithium battery, reduce the system loss, improve the energy efficiency of composite energy storage, and ensure the life of lithium battery. The loss of MPC control strategy is 16.31% less than that of fuzzy control strategy, and the efficiency is 4.91% higher.

References

[1] GEERTSMA R, NEGENBORN R, et al. Design and control of hybrid power and propulsion systems for smart ships: A review of developments[J], Applied Energy, 2017, 194: 30-54. DOI: 10.1016/j.apenergy. 2017. 02 .060.

[2] C. Li, W.Q. Yin, X.B. Feng, et al. Brushless DC motor stepless speed regulation system based on fuzzy adaptive PI controller, Journal of Mechanical & Electrical Engineering, vol. 29 (2012), 49-52.

[3] C.L. Zhu, S.L Yang, et al. Layered coordinated control strategy of lithium battery / super capacitor hybrid energy storage[J], Research and Design of Power Technology, 2019, 10(42): 1672-1675. DOI: 10.3969/j.issn. 1002-087X. 2019. 10. 026.

[4] Y.J Wang, Z.D Sun, Z.D Chen. Development of energy management system based on a rule-based power distribution strategy for hybrid power sources[J], Energy, 2019, 175: 1055-1066. DOI: 10.1016/j.energy. 2019. 03. 155.

[5] M.L Zhou, W.W Zhao, et al. Composite energy storage system and control strategy of pure electric vehicle[J], Journal of Harbin University of Science and Technology, 2018, 23(3): 79-85. DOI: 10.15938/j.ihust.2018. 03. 014.

[6] X.H Lu, K.R Zou. Regenerative braking strategy of pure electric vehicle based on fuzzy control[J], Science Technology and Engineering, 2019, 19(23): 271-275.

[7] D.Z Yao, C.J Xie, et al. Energy management strategy of electric hybrid vehicle based on multi fuzzy control[J], Automobile Engineering, 2019, 42(6): 617-640. DOI:10. 19562 /j.chinasae. qcgc. 2019. 06. 002.

[8] M.L Zhou, J.X Feng, et al. Research on power distribution control strategy of hybrid energy storage system for pure electric bus[J], Journal of Electrical Technology, DOI: 10. 19595/j.cnki.1000-6753.tces.181477.

[9] L.F Yan, J.S Liu, et al. Adaptive power allocation strategy of DC micro grid composite energy storage system based on fuzzy logic algorithm[J], Chinese Journal of Electrical Engineering, 2019, 39(9): 2658-2669. DOI: 10.13334/j.0258-8013.pcsee.172680.

[10] Q Wang, Y.K Sun, et al. Power distribution control strategy of hybrid electric vehicle[J], Journal of Electrical Technology, 2017,32(18): 143-151.

[11] D.J Gao, W Zhang, et al. Energy control strategy of hybrid electric ship based on model predictive control[J], Journal of Shanghai Maritime University, 2018, 39(2): 60-65.

[12] PAPALAMBROU G, et al. Model predictive control for hybrid diesel-electric marine propulsion[J]. IFACPapersOnLine50-1, (2017): 1106411069.DOI:10.1016/j.ifacol. 2017. 08. 2488.

[13] CASTAINGS A, LHOMME W, et al. Comparison of energy management strategies of a battery/supercapacitors system for electric vehicle under real-time constraints[J]. Applied Energy, 2016(163): 190-200. DOI: 10.1016/j.apenergy. 2015. 11. 020.

[14] KHALIGH A, LI Z H, et al. Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: state of the art[J]. IEEE Transactions on Vehicular Technology, 2010., 59(6): 2806-2814. DOI: 10.1109/TVT.2010.2047877.

[15] ROUMILA Z, REKIOUA D, et al. Energy management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery[J]. International Journal of Hydrogen Energy, 2017, 42(30): 19525-19535. DOI: 10.1016/j.ijhydene.2017.06.006.

[16] L Lin, X Jin, et al. State evaluation and control strategy of dual battery system considering the imbalance of charge and discharge energy[J], Power System Automation, 2018, 42(10): 128-134. DOI: 10.7500/AEPS20171107013.

[17] X.C Zhao, Y Guo. Review on energy management strategy of hybrid electric vehicle[J], Journal of Automation, 2016, 42(3):321-333. DOI: 10.16383/j.aas.2016.c150477.

[18] GOLCHOUBIAN P, AZARD N. Real-Time Nonlinear Model Predictive Control of a Battery–Supercapacitor Hybrid Energy Storage System in Electric Vehicles[J]. IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. 2017, 66(11):9678-9687.

[19] CHEN C, HE Y, et al. Equivalent series resistance-based energy loss analysis of a battery semiactive hybrid energy storage system[J]. IEEE TRANSACTIONS ON ENERGY CONVERSION, 2015, 30(3): 1081-1091. DOI: 10.1109/TEC.2015.2418818.