A Thrust Allocation Strategy for Electric Propulsion Ships Based on Model Prediction Control

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Abstract

Human demand for energy conservation and emission reduction drives the development of ships to green and low-carbon. Electric propulsion ships have become one of the current mainstream ship types. The power consumption of electric propulsion system, whether propeller or other high-power load, often changes significantly when it operates in unpredictable marine environment. In this paper, a thrust allocation method based on model predictive control is proposed. Compared with the traditional sequential quadratic programming method, its power consumption is reduced by 10.2%. At the same time, considering the sudden reduction of the power generation capacity of the ship, a power constraint is designed, which can keep the propulsion power of the ship within a limited range and complete the operation of the ship under the condition of meeting the necessary daily use and other loads. Finally, the feasibility of this method is verified by simulation experiments.

Keywords

Electric propulsion ship; Model predictive control; Power system; Thrust allocation.

1. INTRODUCTION

With the characteristics of low energy consumption, low emission and good economy, electric propulsion system has attracted the attention of the shipbuilding industry, and has become one of the main ways of marine propulsion system [1]. The electric propulsion ship is directly driven by the motor propeller, and the ship power station distributes energy according to the navigation state of the ship and the use of other equipment under different working conditions. However, because there are many kinds of loads in the ship's power grid, the criticality of each load under different working conditions and tasks is also different. When the emergency large load suddenly joins the power grid, or the generator suddenly exits the power grid due to fault, it will cause the fluctuation of the frequency of the ship's power grid, and the stability of the ship's power grid is facing great challenges [2].

At present, in view of the fluctuation of the total power consumption of the ship, it is more by forcibly starting additional generator sets or stopping the currently running generator sets, or forcibly unloading some other loads on the ship. This will increase the fuel consumption, wear and maintenance cost of generator sets, and also make the ship's operation more complex [3]. The optimal thrust allocation of multi propeller is one of the effective ways to coordinate the power grid and improve the stability of the power grid [4]. The thrust allocation algorithm can coordinate each propeller to make the thrust output of the propeller meet the needs of different working conditions. In recent years, using thrust allocation algorithm to improve power grid stability has become a research hotspot. T. A Johansen et al. [5] proposed a classical thrust allocation algorithm, which treats the thrust allocation problem as a nonlinear constrained optimization problem, and solves the thrust allocation problem by using sequential quadratic programming (SQP). On this basis, A. veksler [6] uses the power of the propulsion system to compensate the power fluctuation of other loads, and proposes a thrust allocation optimization strategy based on dynamic power load modulation, which effectively reduces the power consumption and the wear of propulsion equipment. S. Kim [7] proposed a thrust allocation algorithm based on penalty programming, which approximates the fuel consumption of diesel generator to the quadratic polynomial of power output to minimize energy consumption.

The traditional thrust allocation method takes the minimum power consumption as the main goal, and does not take into account the impact of power system power consumption and load changes on ship power grid. Based on reference [5], this paper proposes a thrust allocation method. The improved thrust allocation method takes model predictive control (MPC) as the core to realize the thrust optimization of multi propeller electric propulsion ship. At the same time, considering the sudden reduction of the power generation capacity of the ship, a power constraint is designed, which can keep the propulsion power of the ship within a limited range and complete the operation of the ship under the condition of meeting the necessary daily use and other loads. Finally, Matlab simulation is realized to verify the feasibility of the proposed strategy.

2. MATHEMATICAL MODEL OF THRUST ALLOCATION

As the control algorithm of the ship motion system, according to the thrust command given by the control system and combined with the actual working situation of the propeller, the thrust allocation allocates appropriate force to each propeller to resist the external environmental force, so as to minimize the power consumption of the whole ship, and also have strong flexibility and rapidity. When the ship is equipped with azimuth propeller, the thrust allocation problem becomes a multi constraint and nonlinear problem.

The core of thrust allocation problem is that the force allocated to each propeller should match the thrust and torque commands τ_d of the control system in each degree of freedom. The ship is under the action of propeller thrust and wind wave current on the sea. Generally, only the low-frequency motion caused by thrust and wind wave current is considered, and only the motion of the ship in the horizontal plane is analyzed, that is, the three degrees of freedom of surge, sway and yaw [8].

As shown in Figure 1., the ship selected in this paper has four propellers, propellers 1#, 2# and 3# are azimuth propeller, and propeller 4# is channel propeller with positive and negative rotation. The mapping relationship between the control command of the ship controller and the thrust generated by the propellers is as follows [9].

$$B(\alpha)T + s = \tau_d \tag{1}$$

where $\tau_d = \begin{bmatrix} \tau_x & \tau_y & \tau_n \end{bmatrix}^T$ represents the expected surge thrust, sway thrust and yaw thrust moment of the ship controller, $d = [x, y, n]$ represents the three degrees of freedom (surge, sway and yaw), $s \in R^{3\times 1}$ is the deviation between the actual thrust and expected thrust, $T \in R^{4\times 1}$ represents the thrust vector generated by each propeller on board, α is the azimuth of the propeller, $B(\alpha)$ is the configuration matrix of ship propeller with the following expression:

$$B(\alpha)=\begin{bmatrix} \cos\alpha_1 & \mathrm{B} & \cos\alpha_3 & 0 \\ \sin\alpha_1 & \mathrm{B} & \sin\alpha_3 & 1 \\ l_{x1}\sin\alpha_1 - l_{y1}\cos\alpha_1 & \mathrm{B} & l_{x3}\sin\alpha_3 - l_{y3}\cos\alpha_3 & l_{x4} \end{bmatrix} \tag{2}$$

Note that (l_{xi}, l_{yi}) is the coordinate value of the propeller i in the hull coordinate system.

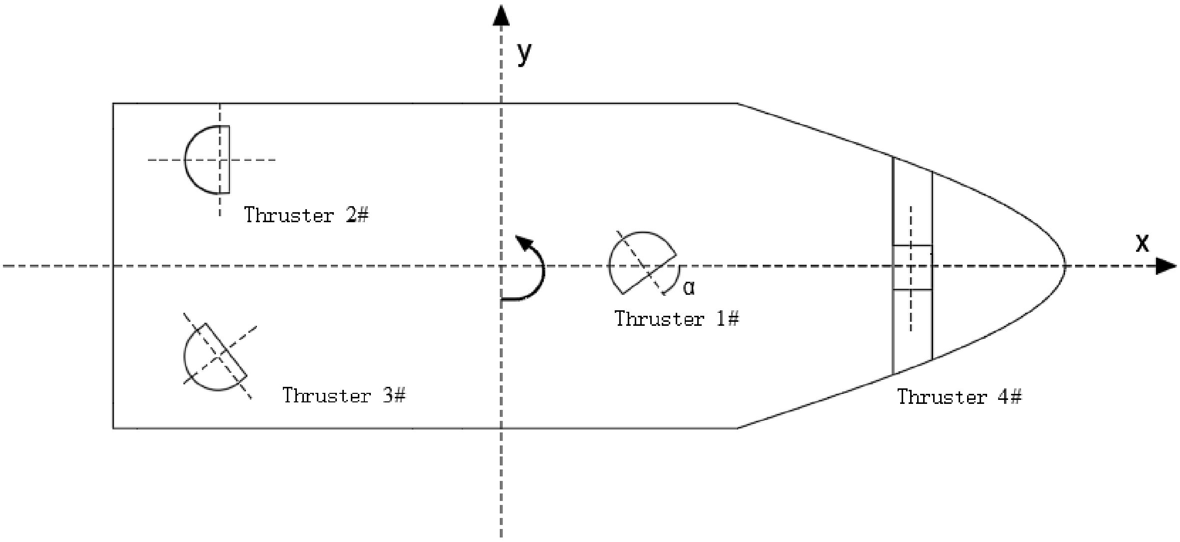

Figure 1. Thruster arrangement

Based on the thruster arrangement in Fig.1, the three degree of freedom forces and moments generated can be expressed as follows:

$$\begin{cases} f_x = f_1\cos\alpha_1 + f_2\cos\alpha_2 + f_3\cos\alpha_3 \\ f_y = f_1\sin\alpha_1 + f_2\sin\alpha_2 + f_3\sin\alpha_3 \\ f_n = -f_1\sin\alpha_1 l_{x1} + f_1\cos\alpha_1 l_{y1} + f_2\sin\alpha_2 l_{x2} + f_2\cos\alpha_2 l_{y2} \\ \quad + f_3\sin\alpha_3 l_{x3} - f_3\cos\alpha_3 l_{y3} - f_4 l_{x4} \end{cases} \tag{3}$$

3. THRUST ALLOCATION ALGORITHM BASED ON MPC

Model predictive control (MPC) is a finite time domain optimal control algorithm based on the controlled object model. It integrates the functions of predictive model, rolling optimization, feedback correction and constraint processing. It can make the controlled system run more smoothly and reduce energy consumption while meeting a variety of constraints [10]. The principle is to take the system state at each sampling time as the current state, predict the future state of the system through the prediction model, solve the current optimal control online according to the given constraints and cost function, and modify it according to the actual output value and the predicted value of the model [11]. Figure 2 shows the control principle of model predictive control.

The traditional thrust allocation method is based on sequential quadratic programming (SQP), which is the most flexible and widely applicable. However, SQP is a numerical method based on gradient. If it is necessary to find long-term optimization objectives within the variation range of propeller state for tens of seconds, the efficiency and accuracy are low. Based on the principle of finite time domain optimal control, MPC can just improve this problem. When MPC is used in thrust distribution problem, its optimization result is more accurate.

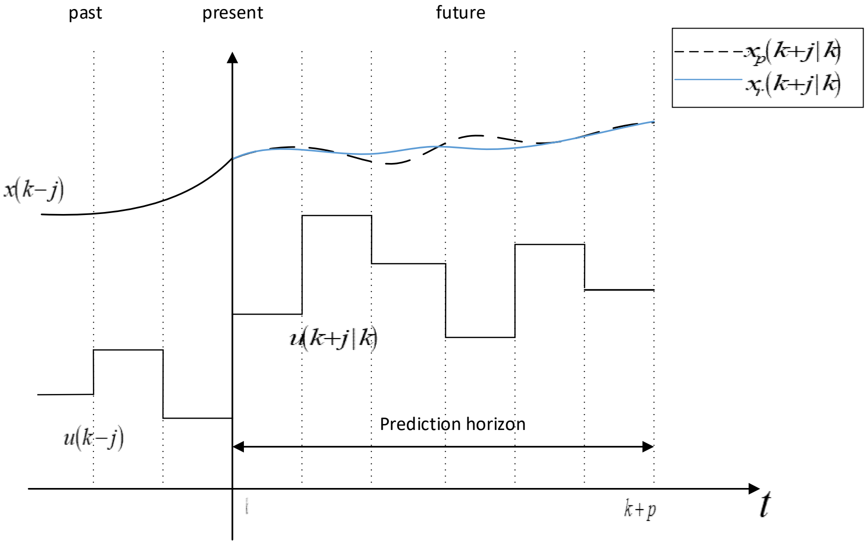

Figure 2. MPC control block diagram

3.1. Constraints

In the thrust allocation method proposed in this paper, various physical limitations need to be considered in the algorithm, which needs to be realized through the constraints in the optimization problem. For electric propulsion ships, there are different types of constraints, which need to be considered in the design of control system.

(1) Thruster mechanical constraints

The thrust size limit of propeller is a hard constraint, which is related to the mechanical performance of propeller. The thrust of the propeller should be set in a range of maximum and minimum values

$$f_{i\min} \le f_i \le f_{i\max} \tag{4}$$

Similarly, the angle of the propeller is limited.

$$\alpha_{i\min} \le \alpha_i \le \alpha_{i\max} \tag{5}$$

Due to the mechanical structure of the propeller, its thrust and angle can not jump, and the change of thrust and angle of the propeller is limited.

$$\Delta f_{i\min} \le \Delta f_i \le \Delta f_{i\max} \tag{6}$$

$$\Delta \alpha_{i\min} \le \Delta \alpha_i \le \Delta \alpha_{i\max} \tag{7}$$

(2) Power Consumption Constrains

The power generation of ship power station is limited, and the power used by propeller is only a part of the total power of ship power station. As shown in Figure 3, the power provided by the power station needs to be provided to the propulsion system, daily use and other loads. When the power generation capacity of the power station decreases sharply, excessive propulsion power will lead to the fluctuation of other load power and affect the stability of ship power grid. The propulsion power can be kept in a limited range by setting power constraints, so that the ship can complete the operation under limited power.

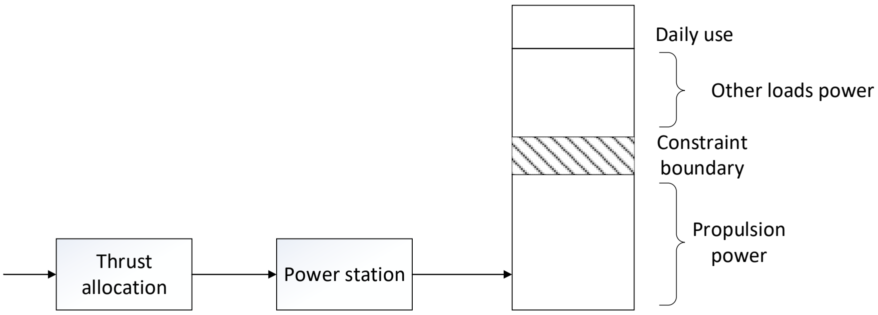

Figure 3. Power distribution of electric propulsion ship

The power consumption of propeller is usually expressed by the function of secondary energy consumption [12]:

$$P_w = \sum_{i=1}^{M} c_i \left| f_i \right|^{\frac{3}{2}} \tag{8}$$

Where, c_i is the power coefficient of the propeller and is the fixed parameter of the propeller.

If the available power of the power station is $P_{\max}$, the power of daily use and other loads is P_{load}, so as to keep the propulsion power within a limited range.

$$P_w \le P_{\max} - P_{load} \tag{9}$$

3.2. Cost Functions

The purpose of multi-step optimization of thrust allocation based on MPC is to obtain the optimal control sequence of propeller i from the initial state x_i to the optimal state x_i^*. For this kind of optimization problem, if the cost function is convex, it is beneficial to the optimization solution and can be obtained by quadratic cost function.

(1) Power Consumption

The load of propeller accounts for a large proportion in the whole electric propulsion system. The change of propeller thrust will have a great impact on the load of the whole power grid. The output power of power system cannot be infinitely low. The output power should be maintained at a certain level in order to maintain stability and safety. What needs to be considered is to minimize unnecessary losses on the premise of ensuring safety and thrust demand.

So the cost function of minimizing power consumption can be expressed by thrust increment.

$$J_P = \sum_{i=1}^{M} c_i \left| f_i \right|^{\frac{3}{2}} \tag{10}$$

(2) Thrust Allocation Error

The thrust allocation algorithm allocates the corresponding state quantity to each propeller according to the control force τ_d, which requires that the thrust provided by all thrusters meet the needs of the controller. A relaxation variable of thrust error s is introduced, and a quadratic penalty term for thrust error is constructed in the objective function.

$$s = \tau_d - \tau \tag{11}$$

$$J_s = s^T Q s \tag{12}$$

where $Q = diag\left(w_x, w_y, w_z\right)$ is a diagonal weight matrix. w_x, w_y is the weight of surge and sway directions， w_z is the weight of yaw direction.

(3) Singularity structure

When the ship is in a strange structure, it will be unable to resist the wind, wave and current disturbance in the yaw direction, and the ship's mobility will be greatly affected. Even when the propeller is not in the state of singular structure, but close to the singular structure, the propeller also needs to produce higher thrust output to meet the needs of working conditions. In essence, it is in exchange for ship mobility by sacrificing propulsion efficiency and consuming more energy [13]. Increasing the thrust output of propeller will lead to the increase of energy consumption and the fluctuation of ship power grid, which can even affect the ship operation. Therefore, it is necessary to introduce a penalty term of singular structure.

$$J_\beta = \frac{\delta}{\varepsilon + \det\left(B(\alpha)B(\alpha)^T\right)} \tag{13}$$

where $\det(A)$ represents the determinant of A. In order to avoid the numerical problem with denominator 0, a minimal parameter ε is introduced. δ is the weight of the singular value penalty term.

In order to avoid unnecessary mechanical wear caused by frequent angle change of rotatable propeller, a penalty term is introduced for angle increment $\Delta\alpha$.

$$J_\Omega = \Delta\alpha^T \Omega \Delta\alpha \tag{14}$$

where $\Omega = \left(w_1, w_2, w_3\right)$ is the penalty matrix of each angle change.

(4) Total MPC Cost Functions

In summary, the thrust allocation objective function based on MPC is as follows:

$$\begin{aligned} J &= \min\left(J_P + J_s + J_\beta + J_\Omega\right) \\ &= \min\left(\sum_{i=1}^{M} c_i \left|f_i\right|^{\frac{3}{2}} + s^T Q s + \frac{\delta}{\varepsilon + \det\left(B(\alpha)B(\alpha)^T\right)} + \Delta\alpha^T \Omega \Delta\alpha\right) \end{aligned} \tag{15}$$

The equality constraints are:

$$\begin{aligned} & f_i(0) = f_0 \\ & \alpha_i(0) = \alpha_0 \\ & f(k) = f(k-1) + \Delta f(k) \\ & \alpha(k) = \alpha(k-1) + \Delta\alpha(k) \end{aligned} \tag{16}$$

The inequality constraints are:

$$\begin{aligned}
&f_{i\min} \le f_i \le f_{i\max} \\
&\alpha_{i\min} \le \alpha_i \le \alpha_{i\max} \\
&\Delta f_{i\min} \le \Delta f_i \le \Delta f_{i\max} \\
&\Delta \alpha_{i\min} \le \Delta \alpha_i \le \Delta \alpha_{i\max} \\
&\sum_{i=1}^{M} c_i \left|F_{ic}\right|^{\frac{3}{2}} \le P_{\max} - P_{load}
\end{aligned} \tag{17}$$

After multi-step optimization of MPC, the optimal thrust increment $\Delta f(k)$ and angle increment $\Delta\alpha(k)$ can be obtained. The optimal thrust vector amplitude is obtained according to the following equations, and finally the optimal thrust amplitude and azimuth angle of each thruster are obtained.

$$\begin{aligned}
f(k) &= f(k-1) + \Delta f(k) \\
\alpha(k) &= \alpha(k-1) + \Delta\alpha(k)
\end{aligned} \tag{18}$$

4. SIMULATION

In order to verify the designed thrust allocation method, a simulation study is carried out on an electric propulsion ship [14].The parameters related to thrusters are shown in Table 1. The control force and control torque required by the simulation setting ship are shown in the Fig.4. The power coefficients of the four propellers are 0.33, 0.37, 0.36 and 0.49 respectively.

Table 1. Thruster parameters

	Thruster position (m)	Maximum thrust (kN)	Minimum thrust (kN)
1#	(22.2,0)	235	-127
2#	(-24.3,-3.3)	365	-273
3#	(-24.3,3.3)	351	-243
4#	(25.2,0)	16	-13

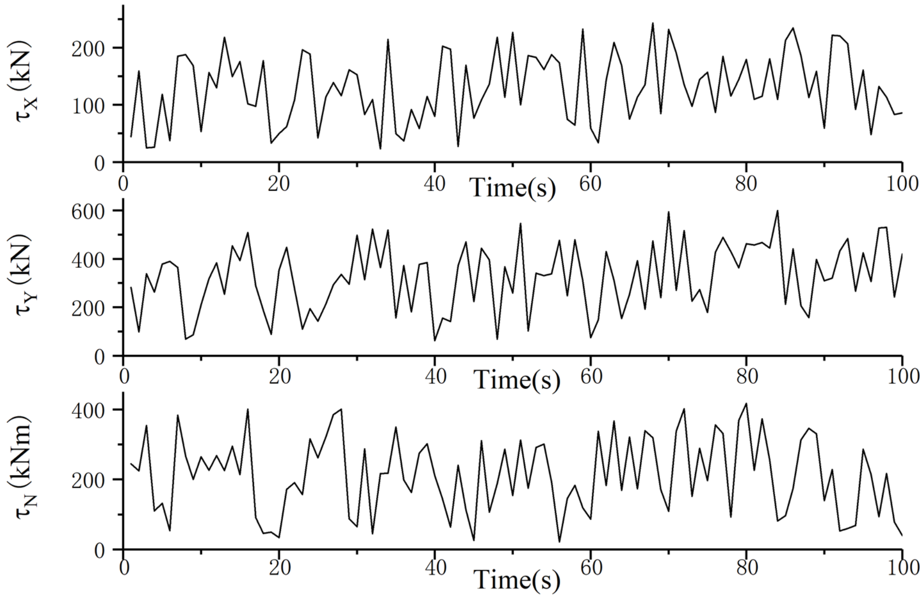

Figure 4. Control force and control torque

As shown in Figure 5, the difference between the thrust allocation method based on MPC and that based on SQP is compared by the total power consumption of the thrusters. The red solid line and blue solid line represent the total power consumption under MPC and SQP respectively. From the simulation curve, it can be seen that the total power consumption of the thrust allocation method based on MPC is less than that of SQP. As shown in Table 2, the average power consumption of SQP is 1747.98kW, while that of MPC is 1569.03kW, which is reduced by 10.2%. The maximum power consumption of SQP is 2978.29kW and the minimum power consumption is 192.19kW, while the maximum power consumption of MPC is 2885.82kW and the minimum power consumption is 161.01kW. Simulation results show that, compared with SQP, the accuracy of MPC is higher and the average power consumption is lower, which indicates that, the proposed strategy based on MPC can obtain higher propulsion efficiency and reduce propulsion power consumption.

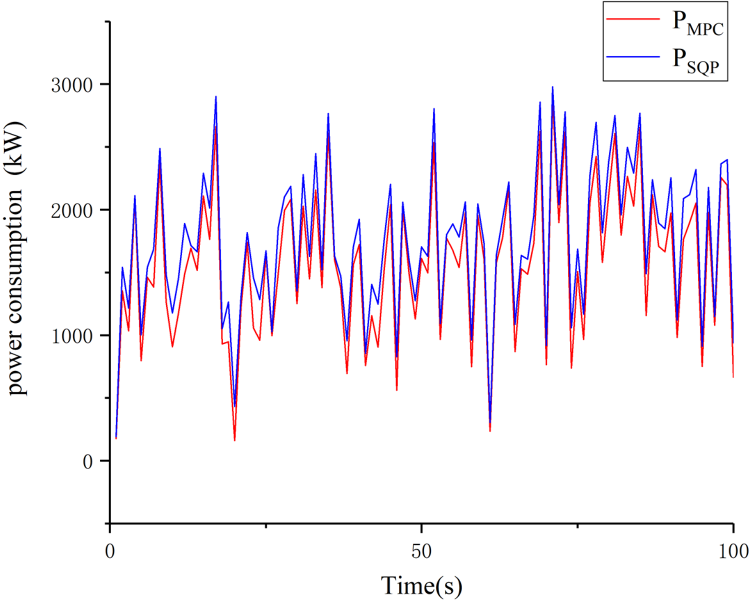

Figure 5. Comparison of power consumption between two algorithms

Table 2. Comparison of power consumption between two algorithms

Algorithms	$P_{\max}$ (kW)	$P_{\min}$ (kW)	P_{ave} (kW)
SQP	2978.29	192.19	1747.98
MPC	2885.82	161.01	1569.03

In the simulation, the available power of electric propulsion ship power station is 3000kW, and the power of daily use and other loads is 1000kW. This article uses two configurations for comparison. In the first configuration, the MPC method is used for thrust allocation, which only considers the mechanical constraints of the propeller, not the power constraints. In the second configuration, the thrust allocation algorithm proposed in this paper considers the power constraint at the same time, and keeps the propulsion power in a limited range. As shown in Figure 6, the thrust allocation algorithm without power constraint will lead to excessive propulsion power and affect the stability of power grid. The thrust allocation algorithm proposed in this paper can make the ship run under limited propulsion power without causing other load fluctuations, which is conducive to improving the stability of ship power grid.

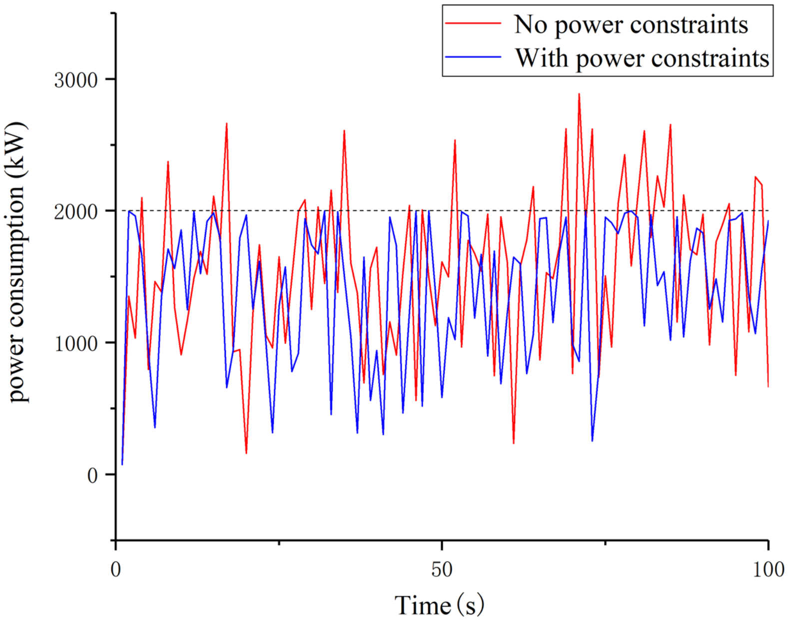

Figure 6. Comparison of power consumption under two configurations

5. CONCLUSION

The thrust allocation method based on model predictive control proposed in this paper is proved by simulation that its power consumption is reduced by 10.2% compared with the traditional thrust allocation method. Furthermore, considering the influence of power consumption and load changes of power system on ship power grid, a power constraint is designed to keep the ship propulsion power in a limited range. The simulation verifies the feasibility of this method.

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