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Sliding Mode Robust Load Frequency Control based on Fuzzy Rules

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Abstract

A sliding mode control method combining with fuzzy rules is proposed in this paper, the primary target of the controller is to reduce frequency fluctuation of power system caused by uncertain factors in ship navigation. The sliding mode compensation controller is designed based on fuzzy rules to approximate the unknown disturbance. the and the parameters is optimized by H∞ theory. The performance of the designed controller is evaluated by utilizing simulation software. Simulation results show, compared with the traditional proportional integral controller, that the proposed sliding mode controller can effectively suppress the system frequency fluctuation, has lower frequency overshoot and faster frequency recovery. It can suppress the parameter uncertainty and the influence of disturbance on the system, which will ensure the system run stably and have good robustness performance.

Keywords

Load Frequency Control; H∞ Theory; Fuzzy Rules; Sliding Mode Control.

1. Introduction

With the increasing demand for electricity and the consciousnes of green environmental protection, the integrated power system has been widely used in the shipping industry [1-2]. The ship integrated power system combines the propulsion system with the power system, which is beneficial to the optimization of the structure layout and the improvement of the fault tolerance rate. Marine electric propulsion system mainly uses several diesel engines as power sources. However, with the diversification and informatization of ship functions, the Marine electric propulsion system needs to meet the requirements of stable operation under various operating conditions and take low emission and high efficiency into account. Therefore, the introduction of a hybrid Marine electric propulsion system composed of an energy storage system is currently a hot research topic [3-4].

The complexity of the Marine environment will lead to the load power fluctuation when the ship is navigation, which will cause the imbalance between the active power of the power system and the actual demand power.Furthermore, it will enhance the risk of frequency instability. Frequency is one of the most important indicators to measure the quality of power and also is an important parameter to maintain the stable operation of power system. The general frequency regulation methods of power system include the configuration of energy storage and control generator set,which has been studied by many reaserchers. In [5,6], a two-layer ADRC method based on estimated equivalent input disturbance compensation is proposed. This method can effectively reduce the influence of random load variation and parameter uncertainty, and maintain good dynamic performance and robustness for the system. In order to realize real-time optimization and constraint enhancement,a constrained MPC optimization problem for the system model is represented in [7,8], which is solved with integrated perturbation analysis and sequential quadratic programming (IPA-SQP) algorithm.The simulation results show that IPA-SQP algorithm can satisfied fast load tracking. But it did not consider the effects of grid frequency changes. In [9], a new fractional-order fuzzy PD+I load frequency controller is designed for isolated microgrid of power system, and it used the improved black hole optimization algorithm to optimize and adjust the coefficients of the non-integer fuzzy PD+I controller, which, compared with the traditional controller,has stronger robustness. According to the event communication mechanism , the corresponding robust controller is studied in [10]. This controller can effectively reduce the impact of random load fluctuations on the system frequency and suppress frequency deviation, but it is not applicable to all load interference.In [11], the application of μ and robust h-infinity control in load frequency control of micro power grid is studied,which had estimated the controller robustness and performance under various perturbations and parametric uncertainties and got very good effect, but the proposed control method is too complex to implement. A battery energy storage system coordinated control strategy with fuzzy theory is presented in [12,13]. The results of the study show that this strategy can quickly respond to frequency changes and reduce frequency deviations, but it does not analyze the effects of unmodeled parts of the power system. Abviously, most of the above studies focus on land power system, and ship power system on account of unit capacity, sailing environment and other uncertainty issues will exist unmodeled part which will break the balance between active power and demand power. Therefore, the designed controller must meet the control accuracy and have a strong robustness.

To sum up, according to variable structure control is insensitive to external disturbance, this study is to present a new sliding mode controller. Considering the model uncertainty and external load disturbance comprehensively, the sliding mode parameters are optimized by h-infinity and fuzzy rules. In order to verify the performance of the controller, a simulation based on ship power system is given in this paper, the result shows the controller have a strong robustness and can reduce load fluctuation efficiently.

2. System Model

In hybrid electric propulsion ships, diesel generator sets is the main energy supply part due to their high power output and security of operation. Battery can effectively ensure the stability of power system power and frequency because of its characteristics of rapid charge and discharge. Servo pump, propeller and other load equipment maintain a stable working state by absorbing the active power on the DC bus. The AC/DC transformation of voltage and current by virtue of power electronic technology such as rectifier, inverter and up-down voltage.

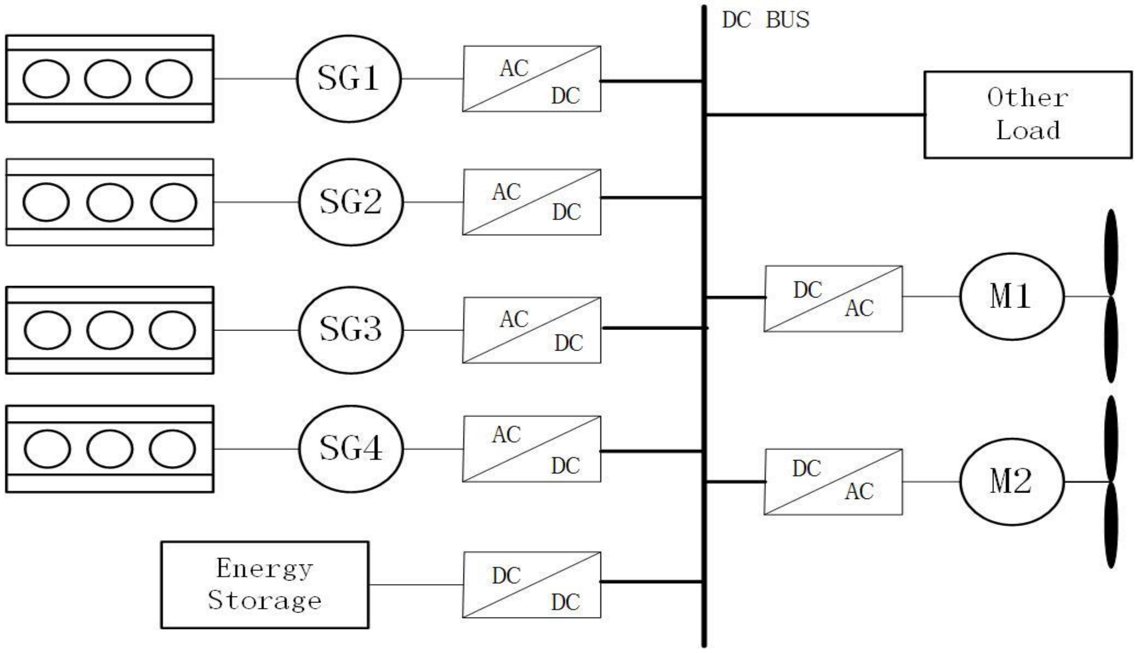


Figure 1. Hybrid electric propulsion system structure

Figure 1 shows the ship hybrid electric propulsion system including the energy storage system. In view of the structure is shown in figure 1, when the power system is stable operation, regardless of the loss, the ship power grid should be in balance, but the load power of the ship can not maintain at a cerition value because of the propulsion motor start, stop, and the instability will cause the change of the generator speed, which will lead the system frequency fluctuations. Mathematically,active power balance of ship's power network can be expressed as:

$$\Delta P = \Delta P_{deg} + \Delta P_{bat} - \Delta P_{d} \tag{1}$$

where, ΔP is the power variable of power grid, ΔP_{deg} is the output variable of diesel engine, ΔP_{Bat} is the power variable of energy storage battery, and ΔP_{d} is the power variable of load disturbance.

When the ship power system is influenced by external load, in order to achieve active power balance and system frequency stability, it is necessary to maintain the system frequency at a certain reference value by primary frequency modulation and secondary frequency modulation. The essence of controlling the system frequency is to control the speed of diesel generator set. In this paper, the ship hybrid electric propulsion system is taken as the research object, and the governor, prime mover, generator-load and energy storage battery are modeled respectively. The specific models are as follows.

The battery model reference [14] as depicted in Figure 2. A low-pass filter(LPF) was designed in front of the speed regulating machine, and the control signal of the battery is calculated by the difference between the output signal of the controller and the diesel generator set.

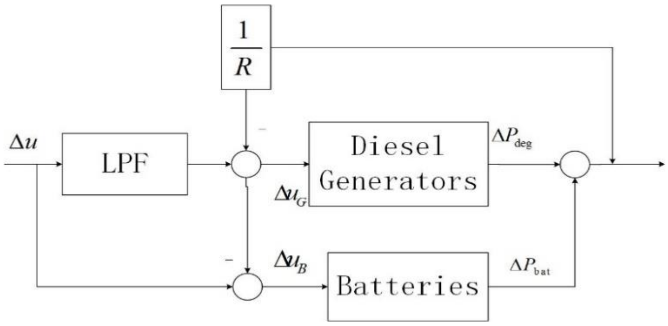


Figure 2. Frequency modulation process of diesel generator with battery

The governor adjusts the valve increment to control the prime mover according to the control increment, and its transmission function can be expressed as

$$\Delta X_g(s) = \frac{1}{T_g s+1}\left(u - \frac{1}{R}\Delta f(s)\right) \tag{2}$$

where u is the system control quantity, T_g is the time constant of the speed-regulating device, ΔX_g is the speed-regulating output variable, Δf is the system frequency deviation, and R is the governor regulation coefficient.

The prime mover converts the fuel chemical energy into mechanical energy to make the generator rotor operate, and its dynamic process transfer function can be expressed as

$$\Delta P_{deg} = \frac{1}{T_{deg}\, s+1}\Delta X_g \tag{3}$$

where T_{deg} is the prime mover time constant.

The linearized motion equation of synchronous generator rotor can be expressed as

$$\begin{cases} M\frac{d\omega}{dt} = \Delta P - D\Delta\omega \\ \frac{d\Delta\delta}{dt} = \Delta\omega \end{cases} \tag{4}$$

After the Laplace transform, the above equation can be expressed as

$$\Delta f = \frac{1}{Ms+D}\Delta P \tag{5}$$

where M is the inertia coefficient, $\Delta\omega$ is the rotational speed increment, D is the damping coefficient, and $\Delta\delta$ is the electric angular velocity increment.

According to the equation (2)-(5), the corresponding load frequency control model of Marine hybrid electric propulsion system is shown in Figure 3.

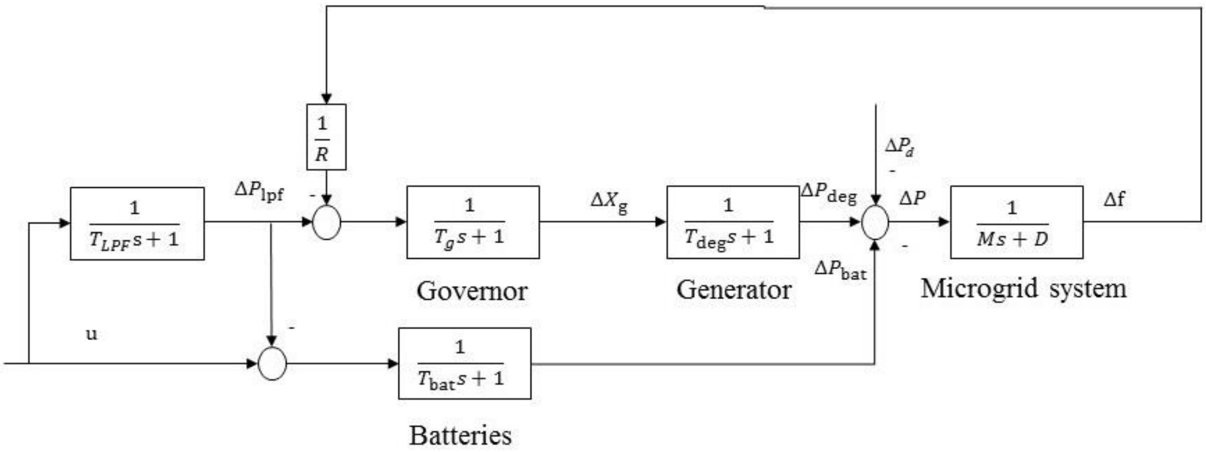


Figure 3. Load frequency control model

According to the LFC system, the equation of state can be established as follows

$$\Delta\dot{f} = \frac{1}{M}P_{deg} + \frac{1}{M}P_{bat} - \frac{D}{M}\Delta f - \frac{1}{M}\Delta P_d \tag{6}$$

$$\Delta\dot{P}_{bat} = \frac{1}{T_{bat}}\Delta P_{LPF} - \frac{1}{T_{bat}}\Delta P_{bat} + \frac{1}{T_{bat}}u \tag{7}$$

$$\Delta\dot{P}_{deg} = -\frac{1}{T_{deg}}\Delta X_{deg} + \frac{1}{T_{deg}}\Delta P_{deg} \tag{8}$$

$$\Delta\dot{X}_g = -\frac{1}{R}\Delta f - \frac{1}{T_g}\Delta X_g + \frac{1}{T_g}\Delta P_{LPF} \tag{9}$$

$$\Delta\dot{P}_{LPF} = -\frac{1}{T_{LPF}}\Delta P_{LPF} + \frac{1}{T_{LPF}}u \tag{10}$$

According to equation (6)-(10), he equation of state can be expressed as

$$\dot{x} = Ax + Bu + DP_d \tag{11}$$

Considering the uncertainty of system parameters caused by load and other factors changing with time in the power system, the model of Formula (11) is rewritten as

$$\dot{\mathrm{x}} = (\mathrm{A} + \Delta\mathrm{A})\mathrm{x} + (\mathrm{B} + \Delta\mathrm{B})\mathrm{u} + (\mathrm{D} + \Delta\mathrm{D})\mathrm{P}_d \tag{12}$$

Where A is the system state matrix, B is the output matrix, D is the system interference term matrix, P_d is the system power interference input, ΔA, ΔB and ΔD is the parameter uncertainty caused by the system uncertainties, x is the state variable, can be expressed as $x^T = \begin{bmatrix}\Delta P_{LPF} & \Delta X_g & \Delta P_{deg} & \Delta P_{bat} & \Delta f\end{bmatrix}$.

3. Sliding mode controller design

3.1 Sliding mode control law

Hybrid electric propulsion system is a small independent power system, which needs to adjust itself to achieve voltage and frequency stability. When the ship power system is working, the different real-time demands will lead to the constant change of load, then it will cause the migration of balance working point and the variation of power system parameters. Sliding mode control has the characteristics of strong robustness and insensitivity that can restrain the influence of load disturbance and system parameter changes [15-16]. In this paper, a corresponding integral sliding mode structure is designed for the system with uncertain parameter, which can be expressed as

$$s = \mathrm{Cx} - \int_0^t \mathrm{C(A + BK)\,x}(\tau)d\tau + \int_0^t K_e \Delta E(\tau)\, d\tau \tag{13}$$

where C is the constant matrix to ensure asymptotic stability of the sliding mode, K is the state feedback matrix, $\varDelta E$ is the integration frequency error gain which can eliminate the frequency static error, K_e is the integration frequency error gain coefficient.

$$\dot{s} = \mathrm{C\dot{x}} - \mathrm{Ax} + \mathrm{BKx} + K_e\Delta E = -\mathrm{CBKx} + \mathrm{CB}u + \mathrm{CDP}_d + K_e\Delta E + \mathrm{Cg} \tag{14}$$

where g is the aggregation term of the uncertain parameters of the system, can be represented as

$$g = \varDelta Ax + \varDelta Bu + \varDelta DP_d \tag{15}$$

When the system is on the sliding surface, it will be $\dot{s} = s = 0$. Considering the robust term of sliding mode control, the sliding mode control law can be designed as

$$u = \mathrm{Kx} - \mathrm{CB}K_e\Delta E - h\,sgn(s) \tag{16}$$

where $h\,sgn(s)$ is the robust compensation term, where sgn is the sign function.

Forthermore, the equation (14) then can be expressed as

$$\dot{s} = \mathrm{CD}P_d + \mathrm{Cg} - h\,sgn(s) \tag{17}$$

In order to ensure the sliding mode stability of the system, it is assumed that the uncertainty term and load disturbance term is norm-bounded. The Lyapunov function can be designed as

$$V = \frac{1}{2}s^T s \tag{18}$$

If the uncertainty term and load disturbance term satisfy the inequation $(\alpha + \beta)\|C\| < h$, the derivative of Lyapunov function can be wriitten as

$$\dot{V} = s^T\dot{s} = s^T\big((\alpha + \beta)\|\mathrm{C}\| - h\,sgn(s)\big) < 0 \tag{19}$$

According to second theorem of Lyapunov, if $V > 0$ and $\dot{V} < 0$, the control system satisfies the stability condition.

3.2 Feedback gain design

This paper utilizes H∞ control theory to optimize the state feedback gain matrix. H∞ theory have a superior benefit for suppressing the influence of system uncertainties and improving the control performance [17]. According to the system in this paper, the signal dynamic equation with evaluation index is established, which is expressed as follows

$$\begin{cases} x = \boldsymbol{Ax} + \boldsymbol{B_1 w} + \boldsymbol{B_2} u_k \\ z = \boldsymbol{C_1 x} + \boldsymbol{D_{11} w} + \boldsymbol{D_{12}} u_k \end{cases} \tag{20}$$

Where z is the system reference output; $\omega \in R^{1\times 4}$ is bounded disturbance; $u_k = Kx$ is static feedback control input. $B_2 = B$ is the system input matrix.

Closed loop transfer function about ω to z can be written as

$$\mathrm{T_{\omega z}}(s) = (\mathrm{C_1} + \mathrm{D_{12}K})[s\mathrm{I} - (\mathrm{A} + \mathrm{B_2K})]^{-1}\mathrm{B_1} + \mathrm{D_{11}} \tag{21}$$

The main goal of H∞ control theory is to find the feedback gain matrix which is capable to ensure the asymptotic stability of the closed loop system and minimize H∞ norm of closed loop transfer function

$$\|\mathrm{T_{\omega z}}(s)\|_\infty = \|(\mathrm{C_1} + \mathrm{D_{12}K})[s\mathrm{I} - (\mathrm{A} + \mathrm{B_2K})]^{-1}\mathrm{B_1} + \mathrm{D_{11}}\|_\infty < 1 \tag{22}$$

Using linear matrix inequality (LMI), The matrix inequality is equivalent as

$$\begin{bmatrix} \mathbf{AX} + \mathbf{B_2W} + (\mathbf{AX} + \mathbf{B_2W})^T & \mathbf{B_1} & (\mathbf{C_1X} + \mathbf{D_{12}W})^T \\ \mathbf{B_1}^{\mathbf{T}} & -\mathbf{I} & \mathbf{D_{11}}^{\mathbf{T}} \\ \mathrm{C_1X} + \mathbf{D_{12}W} & \mathbf{D_{11}} & -\gamma^2\mathbf{I} \end{bmatrix} < 0 \tag{23}$$

where $\boldsymbol{X}$ is a positive definite matrix, γ is a given index and $\boldsymbol{W} = \boldsymbol{KX}$.

3.3 Fuzzy law

The robust control term switch gain is to compensate the system uncertainties and external disturbance in the sliding mode control law equation(16), but the randomness of load fluctuation of ship power system can lead to problems that parameters changes and stable working point migration. Thus, it requires the designed value h is greater than the perturbation of boundary value, which will cause a chattering problem obviously. In order to solve this problem, this paper exert fuzzy control method to switch the designed value h to trace the variation of disturbance. The main structure of fuzzy sliding mode control system is shown in Figure 4.

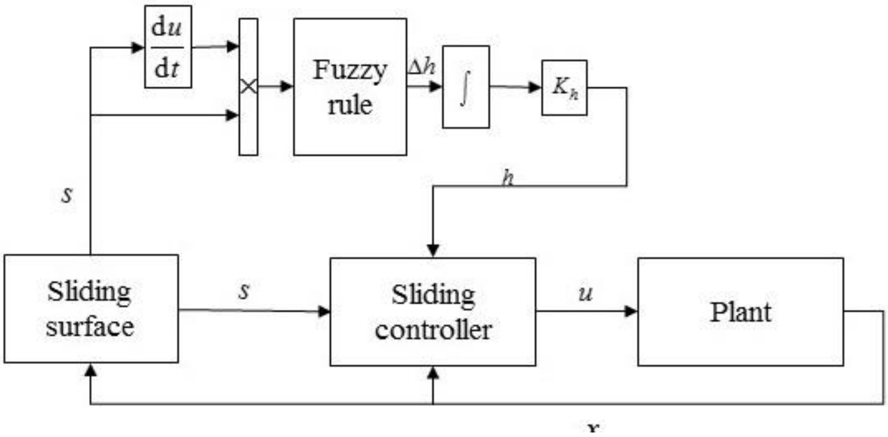


Figure 4. Fuzzy sliding mode control system structure

By considering the fuzzy control scheme of Figure 4, the caculation of designed value can be written as

$$h = K_h \int_0^t \Delta h dt \tag{24}$$

where K_h is the integral proportional gain.

Fuzzification is one of the most important branches of fuzzy law design,thereore,this paper divided the system input and output signals into five hierarchical fuzzy subsets repectively, are assumed as {PB}, {PM}, {ZO}, {NM} and {NB}) that they refer to Negative Small, Negative Medium, Zero, Positive Medium and Positive Large. The membership functions of input and output of the fuzzy system are shown in Figure 5 and Figure 6.

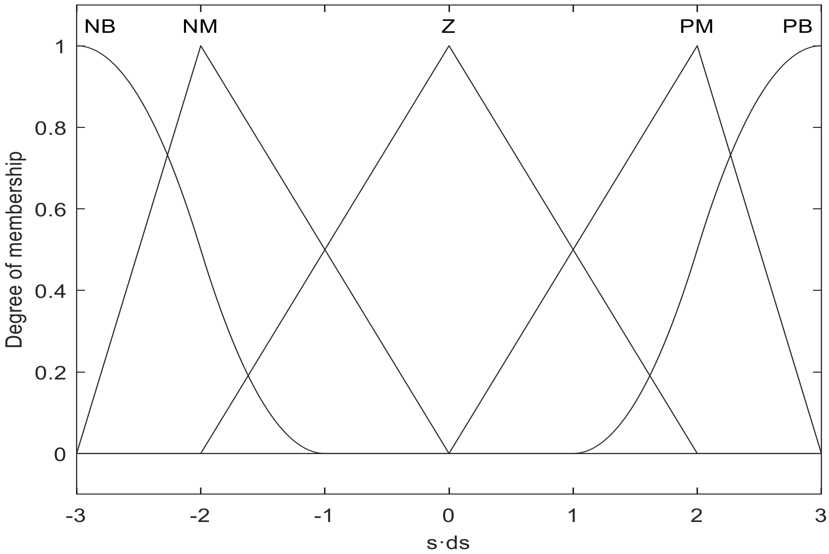


Figure 5. Fuzzy input membership function

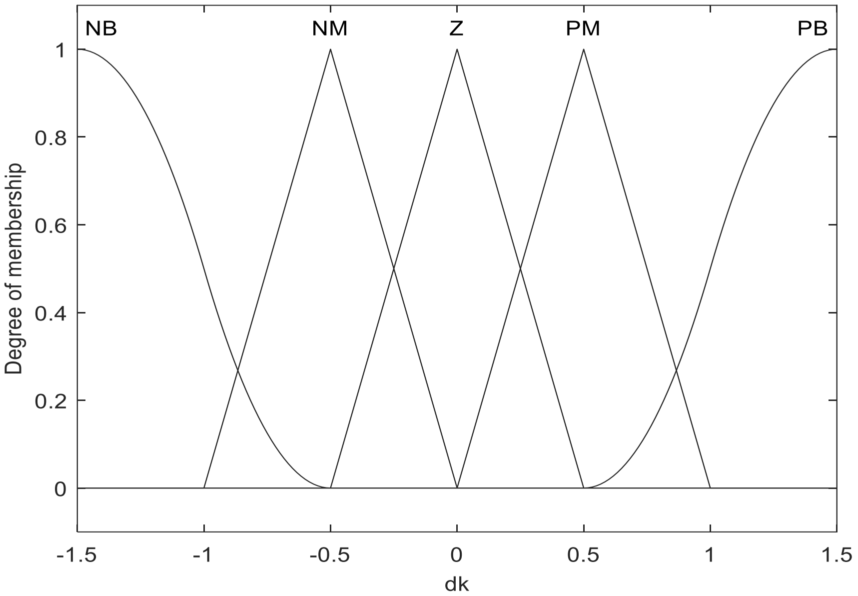


Figure 6. Fuzzy output membership function

Taking the fuzzy process of system variables into account, the fuzzy rules are designed as follows, IF $s\dot{s}$ is PB THEN Δh is PB, IF $s\dot{s}$ is PM THEN Δh is PM, IF $s\dot{s}$ is ZO THEN Δh is ZO, IF $s\dot{s}$ is NM THEN Δh is NM and IF $s\dot{s}$ is NB THEN Δh is NB.

4. Simulation analysis

In this section,for verifying the effectiveness of the proposed fuzzy integral sliding mode controller (FISMC) in the Marine electric propulsion system, a corresponding load frequency control simulation model was built based on Equations (6)-(10). The specific parameters of the system model were selected as shown in Table 1.

Table 1. System parameter

Parameters	Values	Parameters	Values
f	50Hz	T_{bat}	0.2s
T_{LPF}	1.0	M	0.167s
T_g	0.08s	D	0.008s
T_{deg}	0.3s	R	2.4m

At the first step, it is assumed that the system is subjected to step perturbation power $\Delta P_d = 0.1$ p.u. Figure 7 shows the comparison of the dynamic response output of a hybrid power system with battery access and an electric propulsion system without battery access under the traditional PI control method.

As shown in figure 7, the load frequency fluctuation times and the stabilization times of the system are obviously reduced by introducing batteries into the Marine power system. Meanwhile,the power system with batteries is easy to limite the variation of generators via the response characteristics of the battery to the disturbed power of the system.

Figure 8 shows the system power frequency variation under the controller designed in this paper and traditional PI controller. As shown in Figure 8, when the sliding mode controller is utilized under the power disturbance of step load, the maximum frequency deviation of the system is about 0.04p.u, and the frequency can be restored to the criterion value in about 1 seconds. But the maximum frequency deviation of PI control of the system can reach about 0.1p.u, and it takes about 4 seconds for the system frequency to recover the reference value. Meanwhile, compared with the traditional PI control, the controller designed in this paper can adjust the output power of the diesel engine faster, so that the output power of the system can reach the balance with the demand power. In addition, according to the battery power change curve, the operation depth of the battery under PI control is about 3 times that of FISMC. Therefore, the FISMC control mode can reduce the configuration of the battery capacity.

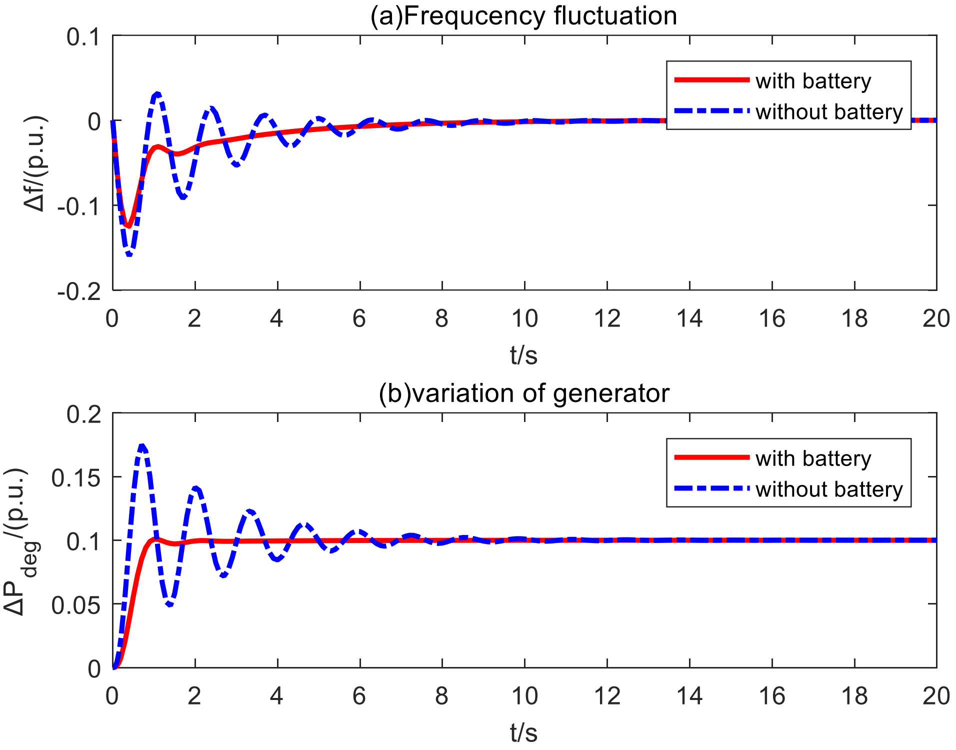


Figure 7. System output response with battery and without battery

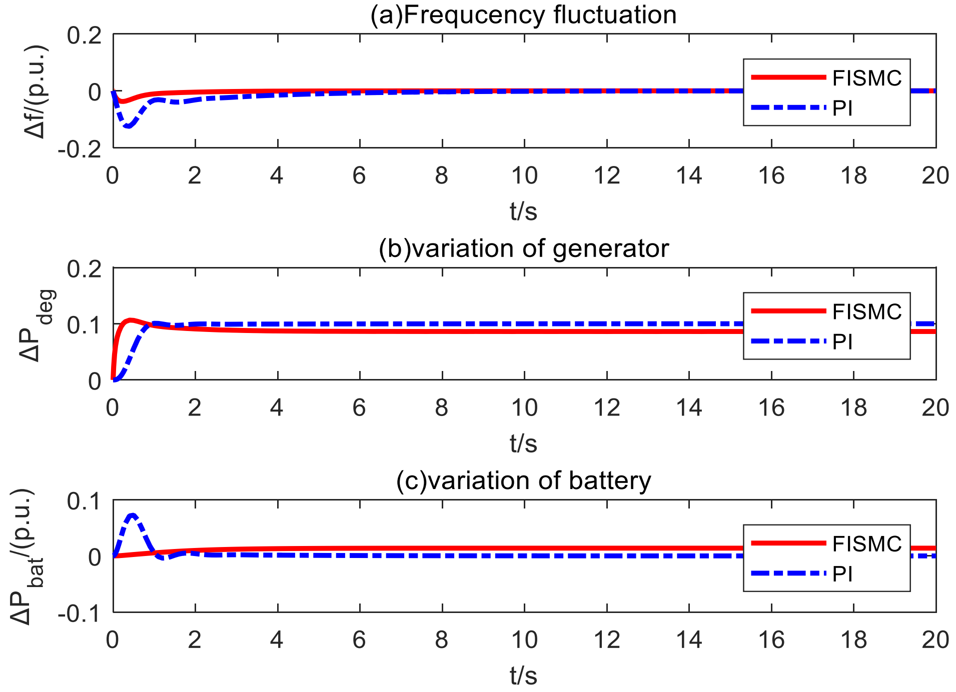
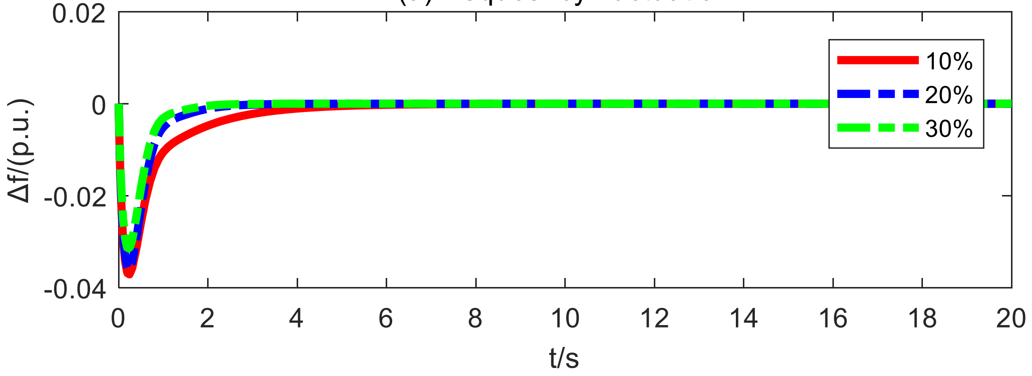
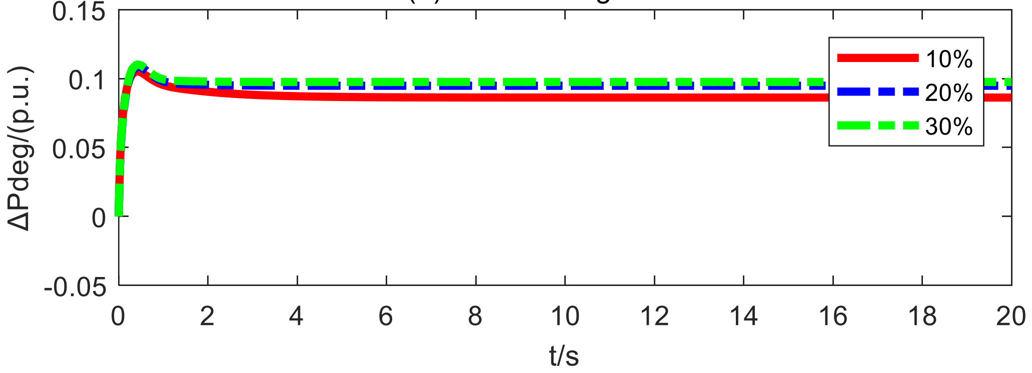


Figure 8. System power frequency variation under load perturbation



(a)Frequcency fluctuation



(b)variation of generator

Figure 9. System output response with parameters perturbation

Assuming that the system parameters are perturbed by 10%, 20% and 30% respectively, the dynamic output response of the system is shown in Figure 10. It can be seen from the Figure. 9, when the parameter is perturbed by 10%, its dynamic response has little change from that of the nominal system. When the parameter perturbation is 20%, the overshoot of frequency response is increased by about 0.002Hz, and the stabilization time is extended by about 0.5s. When the parameter perturbation increases to 30%, the frequency response overshoot of the system increases by about 0.003Hz, and the stability time is extended to about 4 s, but it still has a good stability performance. From the output response of the prime mover, under the condition of parameter perturbation, the dynamic output has been little change, stable running, and the output of the battery power changes greatly, and the parameter perturbation reaches 30%, still has a small range of fluctuations in the process of stability, this is due to the design of low pass filter will have a power fluctuations of parameter perturbation, adjusted by the battery, as far as possible the guarantee of the prime mover and stable operation, reduce its variable load operation is helpful to improve the efficiency of engine fuel, reduce exhaust emissions.

5. Conclusion

A secondary frequency-modulated sliding mode controller for Marine hybrid electric propulsion system with implicit battery is presented in this paper. The controller concentrates to solve the problem of system frequency deviation caused by parameter uncertainty and load power disturbance. In order to restrain the time-varying characteristics of disturbance, the fuzzy rules are adopted to adjust the parameters of the controller in real time, so that the controller has stronger adaptability. The simulation results show that the controller can respond to the load disturbance of the power system quickly and ensure the system frequency has a small overshoot. In addition, the designed controller is insensitive to system parameter perturbation, which greatly enhances the robustness of the system and extremely reduces the risk of unstable operation of the system .

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