Fuzzy Systems and Data Mining IX
A.J. Tallón-Ballesteros and R. Beltrán-Barba (Eds.)

doi:10.3233/FAIA231082

Research on Harmonic Suppression Method Based on Control Active Filter in Ship Integrated Power System

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Abstract. With the continuous development of power transmission technology and automation control technology, the application of high-power inverter devices in modern ship power systems is increasing. Moreover, as the ship operates under different conditions such as cruising and platform lifting, the degree of harmonic pollution in the ship's electrical grid varies. If harmonics in typical operating conditions like cruising and platform lifting are not effectively managed, it can seriously affect the safe operation of the ship. To address this issue, this paper proposes an intelligent harmonic suppression method for active power filters based on fuzzy PID and model predictive control. It combines fuzzy control with conventional PID control to enhance control robustness. The optimization objective in the model predictive current control is shifted from compensation current provided by the active power filter to the inverter output voltage. By adjusting the phase of the inverter output voltage corresponding to the voltage vector reference value, the range of inverter output voltage vectors participating in rolling optimization is narrowed, thereby achieving control of harmonic currents. Finally, by modeling the ship's integrated power system and simulating two operating conditions, cruising and platform lifting, this study analyzes voltage waveforms and harmonic content before and after harmonic suppression using fuzzy PID and model predictive control active power filters. The results demonstrate that the proposed method can significantly improve voltage quality in power systems under power supply voltage distortion and has excellent harmonic suppression effects.

Keywords. Ship power grid; Active power filter; Fuzzy PID control; Model predictive voltage control

1. Introduction

Different from land transportation, ships, as a means of transportation for maritime trade, are an independent control system when sailing at sea. With the rapid development of automation technology and power electronics technology theory and put into practical use, the independent ship power system composed of power supply device, power distribution device, power grid and load is more and more frequently used in ships [1]. In order to maintain the high quality of the ship 's power grid, it is required that the

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amplitude, frequency and phase of the ship 's power grid voltage can quickly restore stability when encountering large changes such as sudden changes. The capacity and . quantity of ship power electronic devices have increased greatly, which improves the performance advantages of ships, and inevitably leads to the harmonic problem of ship power grid [2]. The harmonics of the ship 's power grid bring more and more safety hazards and ship operating costs. The harmonic pollution of the ship 's power grid will bring many negative effects, including the decline of the power quality of the ship 's power system, the reduction of the power efficiency, the reduction of the transmission capacity of the system, the reduction of the service life of the equipment connected to the system, the safety hazards of the power system and the electrical equipment, and the reduction of the operation efficiency [3]. Therefore, it is an inevitable trend to suppress the harmonics of the ship power grid and improve the power quality of the power grid.

The harmonic suppression methods of ship power system are divided into active [2] and passive [4]. The active harmonic suppression method is to transform the harmonic source device itself, such as the power electronic devices carried by the ship, such as frequency conversion devices. The active harmonic suppression method cuts off the harmonics from the source or greatly reduces the harmonic output. Because electric propulsion technology has more advantages in speed regulation performance, most ship power systems will use electric propulsion technology instead of diesel engine propulsion technology in the future [5]. The passive harmonic suppression method is not aimed at the harmonic source itself. It uses the filter to filter out the harmonics at the initial location of the harmonic source, which can theoretically reduce the harmonic content input to the ship power grid [6]. Passive power filter is divided into passive power filter, active power filter and hybrid power filter [7]. The design of old ships is simple, and it is better to use passive power filter for harmonic control. However, the design of modern ships is complex, and the structural characteristics of passive power filters are limited, which is not suitable for modern ship power systems. Modern ship power system harmonic suppression using more active power filter [8].

In view of this, a lot of research has been done at home and abroad. In Reference [9], the method of integrating neural network and fuzzy control and then applying it to APF compensation current control is adopted. In Reference [10-12], the sliding mode variable structure control is applied to the ship electric propulsion system, which improves the harmonic pollution of the system and proves the practicability of the method. However, the serious problem is the high accuracy of the chattering phenomenon damage control. In Reference [13], the active power filter based on fuzzy sliding mode control is applied to the ship electric propulsion system, which reduces the harmonic input of the inverter to the power grid. References [14-15] used repetitive control APF to repeatedly correct the output current signal, and finally achieved the purpose of completely erasing the steady-state error. However, because it is an inherent controller based on periodic type, it is difficult to avoid a periodic delay in control.

The main work of this paper is to model the ship 's integrated power system, and use the system to carry out an example simulation to realize the detection of harmonics in the ship 's operating conditions. The results prove the correctness of the simulation model and method.

2. electric propulsion system

2.1. Structure of ship electric propulsion system

In this paper, the simulation system is used to simulate a ship power system. The single line diagram of the example is shown in the figure. The power generation unit of the system consists of five diesel generator sets, including four main generators and one auxiliary generator. The power of the main generator is 4400 kW and the power of the auxiliary generator is 1600 kW. The AC propulsion system adopts AC-DC-AC frequency conversion, and the rectification part adopts 12-pulse rectification. In addition to the daily load, the system also includes the main propulsion motor, the side thrust motor and the lifting system, and the running state of each equipment under different working conditions is different.

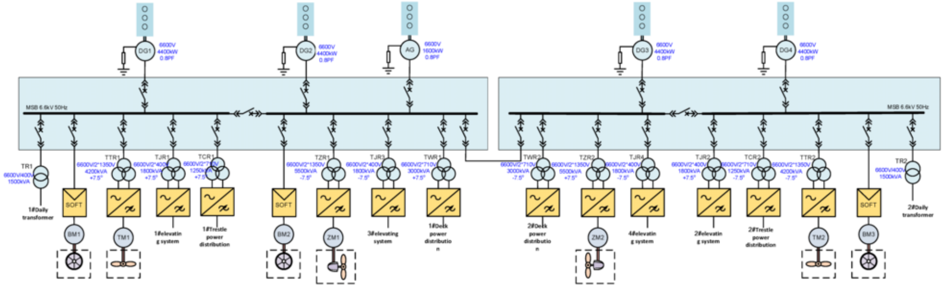

Figure 1. Single-line diagram of ship electric propulsion system.

2.2. Modeling of shunt active power filter

The three-phase three-wire grid topology is usually used in the ship power system, and the parallel active power filter can produce better harmonic control effect, as shown in the figure. The three-phase grid voltage is U_a, U_b and U_c ; the three-phase grid current is i_{1a}, i_{1b} and i_{1c} ; the three-phase load current is i_{2a}, i_{2b} and i_{2c} ; i_a, i_b, i_c provide three-phase compensation current for APF ; u_a, u_b and u_c are the output three-phase voltages of the inverter. C is the DC-side capacitor, and U_{DC} is the DC-side voltage ; L is the AC side inductance ; R is the inductance parasitic resistance ; IGBT is a power switch tube.

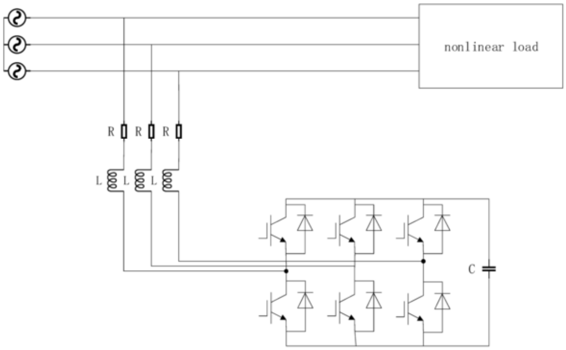

Figure 2. Three-phase three-wire shunt APF topology structure.

According to Kirchhoff 's voltage law, the mathematical model of APF is :

$$\begin{cases} L\, di_a/dt = u_a - \mathrm{U}_a - i_a R \\ L\, di_b/dt = u_b - \mathrm{U}_b - i_b R \\ L\, di_c/dt = u_c - \mathrm{U}_c - i_c R \end{cases} \tag{1}$$

In order to convert the mathematical model from the three-phase coordinate system to the two-phase coordinate system, the Clarke transformation of equation (1) can be obtained :

$$\begin{cases} L\, di_\alpha/dt = u_\alpha - \mathrm{U}_\alpha - i_\alpha R \\ L\, di_\beta/dt = u_\beta - \mathrm{U}_\beta - i_\beta R \end{cases} \tag{2}$$

In the formula : $i_\alpha, i_\beta, u_\alpha, u_\beta$ and e_α, e_β are the three-phase compensation current provided by APF, the three-phase voltage output by the inverter and the three-phase grid voltage components in α , β coordinate systems, respectively.

3. Harmonic suppression strategy of ship electric propulsion system

3.1. Active power filter based on fuzzy PID control

In the face of nonlinear load in ship electric propulsion system, it is impossible to achieve high precision control by using fuzzy theory and PID algorithm alone. In order to improve the control effect of power system, according to the combination optimization theory, combined with the advantages of fuzzy theory and PID algorithm, a control method of power system based on fuzzy theory and PID algorithm is designed. The K_p, K_i and K_d values are optimized online by fuzzy theory to track the state of power system, so that the ship electric propulsion system can be suitable for different working conditions. The control principle is shown in the figure.

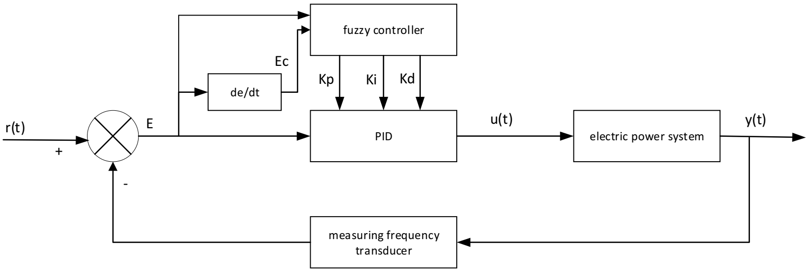

Figure 3. Fuzzy PID Control Block Diagram.

There is a great relationship between K_p, K_i, K_d and e, e_c, the formula is as follows.

$$\begin{gathered} K_p = K_p' + \Delta K_p = K_p' + \{e, e_c\}_p \\ K_i = K_i' + \Delta K_i = K_i' + \{e, e_c\}_i \\ K_d = K_d' + \Delta K_d = K_d' + \{e, e_c\}_d \end{gathered} \tag{3}$$

The pre-setting values of the controller are K_p'、 K_i'、 K_d', and the correction values of the parameters are ΔK_p， ΔK_i、 ΔK_d. The fuzzy PID controller first detects e and e_c in real time to ensure accurate detection, and corrects ΔK_p， ΔK_i and ΔK_d in real time, so that e and ec can meet the needs of Kp, Ki and Kd changes when they change. The correction of the parameters is based on the set fuzzy control rule table.

3.2. APF Model Predictive Control (MPC)

Model Predictive Control (MPC) is a predictive control method based on discretized mathematical models. It is a novel digital control technique. The essence of MPC is an online optimization-based control approach, offering advantages such as fast response and adaptability to changing control objectives.

3.2.1 APF Model Predictive Current Control

In the three-phase three-wire parallel active power filter (APF), the switching states of the three-phase inverter are limited, and the optimal switching state is selected from the limited set of switching states within one sampling period. This control method follows the conventional finite-set model predictive control approach. For APF model predictive current control, it typically involves two main steps: prediction model establishment and rolling optimization.

Prediction Model Establishment: To obtain the predicted compensation current for the next inverter output, it is necessary to establish a prediction model. Based on the mathematical model of the APF, the prediction model can be represented as follows:

$$\begin{cases} u_{ca} = e_a + L\frac{di_{ca}}{dt} + i_{ca}R \\ u_{cb} = e_b + L\frac{di_{cb}}{dt} + i_{cb}R \\ u_{cc} = e_c + L\frac{di_{cc}}{dt} + i_{cc}R \end{cases} \tag{4}$$

Performing a Clark transformation on Equation (4) and representing it after the transformation can be translated as

$$\begin{cases} u_{c\alpha} = e_\alpha + L\frac{di_{c\alpha}}{dt} + i_{c\alpha}R \\ u_{c\beta} = e_\beta + L\frac{di_{c\beta}}{dt} + i_{c\beta}R \end{cases} \tag{5}$$

APF Model Predictive Current Control (MPCC) requires the establishment of a discrete mathematical model for APF. Therefore, discretize equation (5), set the system sampling time to T_s, and expand it using Euler forward difference as follows

$$\begin{cases} i_{p\alpha}(k+1) = \frac{T_s}{L}[u_{c\alpha}(k) - e_\alpha(k) - i_{c\alpha}(k)R] + i_{c\alpha}(k) \\ i_{p\beta}(k+1) = \frac{T_s}{L}\left[u_{c\beta}(k) - e_\beta(k) - i_{c\beta}(k)R\right] + i_{c\beta}(k) \end{cases} \tag{6}$$

Among them, $u_{c\alpha}(k)$ $u_{c\beta}(k)$ are the sampling values of the inverter output voltage at time k . $e_\alpha(k)$、 $e_\beta(k)$ is the sampling value of the grid voltage at the time k . $i_{c\alpha}(k)$、 $i_{c\beta}(k)$ is the sampling value of the compensation current at the moment $k+1$. $i_{p\alpha}(k+1)$、 $i_{p\beta}(k+1)$ is the predicted value of compensation current at time $k+1$. After sorting, the relationship between the predicted compensation current at time k and the sampling values of various variables at time $k+1$ can be obtained as follows:

$$\begin{cases} i_{p\alpha}(k+1) = \frac{T_s}{L}[u_{c\alpha}(k) - e_\alpha(k) - i_{c\alpha}(k)R] + i_{c\alpha}(k) \\ i_{p\beta}(k+1) = \frac{T_s}{L}\left[u_{c\beta}(k) - e_\beta(k) - i_{c\beta}(k)R\right] + i_{c\beta}(k) \end{cases} \tag{7}$$

According to equation (7), it can be seen that using the grid voltage sampling value, compensating for the current sampling value and inverter AC side transmission. By obtaining the voltage sampling value, the predicted compensation current at the next sampling time can be obtained.

3.2.2 APF Model Predictive Voltage Control

Substitute the output voltage vectors of inverters with different effects into equation (7) to obtain the predicted compensation current provided by APF at the time $k+1$. Due to the high sampling frequency of MPC, in order to reduce the number of calculations for the compensation current prediction value provided by APF in one sampling cycle, shorten the program running time, and improve the system's response speed in one sampling cycle, APF Model Predictive Voltage Control (MPVC) changes the variables in the value function based on the advantage of variable MPC control objectives, Change the compensation current provided by APF in the value function to the inverter output voltage. According to equation (7), it is assumed that the predicted compensation current provided by APF at time $k+1$ is equal to the reference compensation current provided by APF obtained from equation.

$$\begin{cases} i_{c\alpha}^{*}(k+1) = 3i_{c\alpha}^{*}(k) - 3i_{c\alpha}^{*}(k-1) + i_{c\alpha}^{*}(k-2) = i_{p\alpha}(k+1) \\ i_{c\beta}^{*}(k+1) = 3i_{c\beta}^{*}(k) - 3i_{c\beta}^{*}(k-1) + i_{c\beta}^{*}(k-2) = i_{p\beta}(k+1) \end{cases} \tag{8}$$

The value function that allows the output voltage of the inverter to be used as the control objective is

$$g = \frac{T_s^2}{L^2}\left[u_{c\alpha}^{*}(k) - u_{c\alpha}(k)\right]^2 + \frac{T_s^2}{L^2}\left[u_{c\beta}^{*}(k) - u_{c\beta}(k)\right]^2 \tag{9}$$

At this point, by controlling the output voltage of the inverter, the compensation current provided by the APF can be controlled. This process reduces the process of converting the output voltage of the inverter into the predicted compensation current provided by the APF through equation (7) within one sampling period, simplifies the computational complexity within one sampling period, and improves the system response speed.

In APF MPVC, the tracking control of harmonic current is indirectly achieved by changing the variables in the value function, and the process of calculating the predicted compensation current provided by APF through the inverter output voltage is omitted. Reduced the computation time within the sampling period and improved response speed. The sampling frequency of MPC control is high and the sampling period is short. APF harmonic current control requires high real-time performance, and the control algorithm needs to be further optimized to reduce the computational pressure of the main control chip. Moreover, the problem with high sampling frequency is that the switching frequency increases and the switching loss increases. To address the above issues, the process of rolling optimization is further optimized. Based on the idea of space vector pulse width modulation (SVPWM), the sector in the inverter output reference voltage vector graph where the voltage vector corresponding to the inverter output reference value is located is judged. The effective vector and zero vector adjacent to the voltage vector corresponding to the inverter output voltage reference value are selected as candidate vectors for rolling optimization.

Four alternative inverter output voltage reference vectors were selected, and during the rolling optimization process, the number of calculations to obtain the minimum value of the value function was reduced from 7 to 4, taking into account both zero vectors with the same effect. Simplified the rolling optimization process. To solve the problem of high switching frequency and high switching loss caused by high sampling frequency, and to achieve multi-objective control of compensating current tracking and switching frequency, a switching frequency control term is added to the value function to add switching frequency constraints when selecting the optimal voltage vector among alternative voltage vectors. The newly established value function :

$$g = \frac{T_s^2}{L^2}[u_{c\alpha}^*(k) - u_{c\alpha}(k)]^2 + \frac{T_s^2}{L^2}\left[u_{c\beta}^*(k) - u_{c\beta}(k)\right]^2 + K_s\{|S_a^*(k) - S_a(k-1)| + |S_b^*(k) - S_b(k-1)| + |S_c^*(k) - S_c(k-1)|\} \quad (10)$$

Among them, S_a^*、 $S_b^*(k)$ and $S_c^*(k)$ is the switching state of each bridge arm corresponding to the reference vector inverter at time k,$S_a(k-1)$、 $S_b(k-1)$、 $S_c(k-1)$ is the switching state of each bridge arm corresponding to the inverter in the previous sampling period, and K_s is the weight coefficient. By adjusting the weight coefficient K_s , the weight occupied by compensating current tracking control and switching frequency control during the online optimization process can be controlled to balance the effectiveness of compensating current tracking control and switching frequency control. The value of K_s is usually determined through multiple simulations and experimental results. The improved APF MPVC principle is shown in Figure 4.

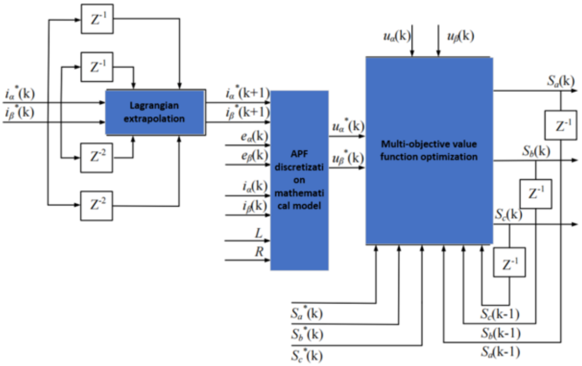

Figure 4 Schematic Diagram of Improved APF MPVC

4. Simulation verification and analysis

4.1. Simulation Results and Analysis of Fuzzy PID Active Power Filter

Harmonics are components of a current or voltage waveform where the frequency is a multiple of the fundamental frequency (usually the grid frequency). These harmonic currents can cause voltage distortion in the power grid, affecting the stability and reliability of the power system. Harmonics may also cause interference to other equipment and users. Therefore, the impact of nonlinear loads on harmonics in the power grid is very important.

Due to the different operating conditions of the equipment in the ship's electric propulsion system, the loads in the circuit will also vary, and the harmonic components are relatively complex. Compared with traditional control methods, for the fuzzy PID control strategy, the harmonic content of the system under cruise conditions and platform lifting conditions was analyzed separately.

Under cruising conditions, three 4400kw generators and one 1600kw generator operate on the grid, while two main propulsion motors with a power of 2300kw and a low-voltage load of 1500kw operate on the grid. The results of using fuzzy PID active filter before and after harmonic suppression in ship electric propulsion system are shown in Figure 5 and Figure 6.

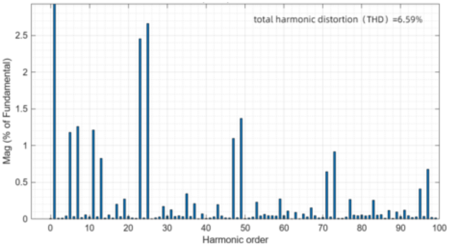

Figure 5. The harmonic content before suppressing the fuzzy PID active filter under cruising conditions.

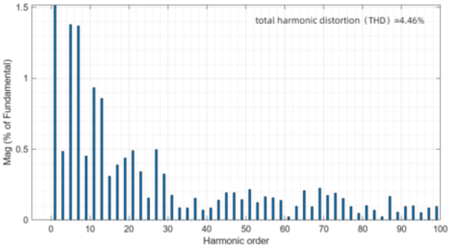

Figure 6. The harmonic content after suppressing the fuzzy PID active filter under cruising conditions.

Two 4400kw generators, one 500kw elevator, and a low voltage load of 1800kw are operating on the grid under the condition of lifting the platform. The results of using fuzzy PID active filter before and after harmonic suppression in ship electric propulsion system are shown in Figure 7 and Figure 8.

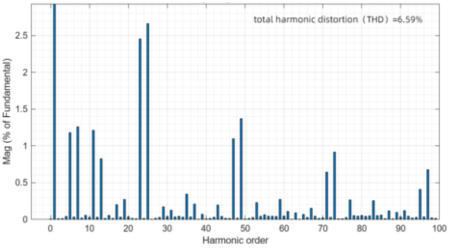

Figure 7. Harmonic content before suppression of fuzzy PID active filter under elevated platform operating conditions.

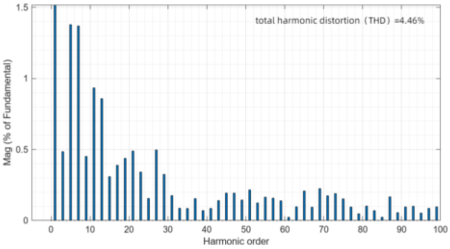

Figure 8. The Harmonic Content of Fuzzy PID Active Filter Suppressed under Elevated Platform Condition.

Figures 5 and 7 show the harmonic content of the ship's electric propulsion system under cruising and platform raising conditions, respectively. Figures 6 and 8 show the harmonic content after suppressing using fuzzy PID active filters under cruising and platform raising conditions, respectively. The voltage distortion rate THD before cruise control is suppressed is 6.59%, and the maximum single harmonic value is 2.75%. After suppression, the voltage distortion rate THD is 4.46%, and the maximum single harmonic value is 1.76%; The voltage distortion rate THD before suppression under elevated platform conditions is 7.36%, and the maximum single harmonic value is 1.97%. After suppression, the voltage distortion rate THD is 4.54%, and the maximum single harmonic value is 1.88%. From the figure, it can be seen that the total voltage distortion rate of both operating conditions after using fuzzy PID active filter suppression does not exceed 5%, and the maximum value of single harmonic does not exceed 3%, meeting the standards of China Classification Society for total harmonic distortion rate.

4.2. Simulation Results and Analysis of Model Predictive Control Active Power Filter

Due to the complexity of harmonic components in equipment such as the main propulsion motor, the frequency converter of the full rotation thruster motor, and the frequency converter of the pile leg lifting device air compressor under the lifting platform working condition during cruising, not only integer multiples of harmonics are included, but also fractional harmonics. These types of devices generally have higher power, and with the increasing use of frequency conversion speed regulation, the harmonics caused to the power grid are also increasing. This article establishes a Matlab simulation model for parallel active power filters based on the topology structure of three-phase three-wire parallel active power filters (Figure 2) and the control system of active power filters (Figure 4). The system parameters of the active power filter are as follows:

Table 1. Active Power Filter System Parameters

Grid line voltage	resistance	inductance	L	R	C	U_{dc}	sampling frequency	K_s
710V	15*Ω*	3mH	1.5mH	0.15*Ω*	3300μF	1050V	15kHz	0.15

The harmonic content after using APF MPVC suppression under cruise and platform up conditions is as follows:

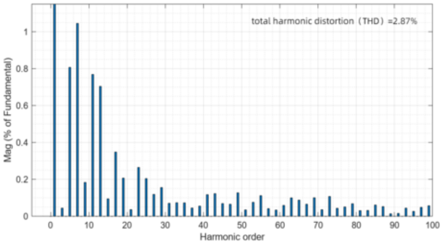

Figure 9. Model predictive control of harmonic content after active filter suppression under cruising conditions.

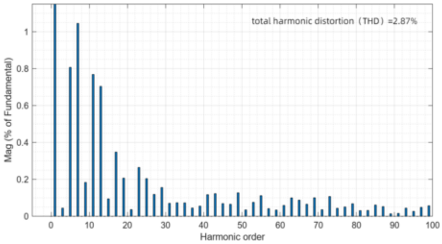

Figure 10. Model predictive control of harmonic content after active filter suppression under elevated platform operating conditions.

Under cruising conditions, the model predictive control active filter is used to suppress the voltage distortion rate THD=2.87%, and the maximum single harmonic value is 1.73%; Under elevated platform conditions, the model predictive control active filter is used to suppress the voltage distortion rate THD=3.39%, and the maximum single harmonic value is 1.40%. From the figure, it can be seen that the total voltage distortion rate of both operating conditions after using model predictive control active filter suppression does not exceed 5%, and the maximum value of single harmonic does not exceed 3%, meeting the standards of China Classification Society for total harmonic distortion rate, and the suppression effect is better than that of fuzzy PID active filter.

Table 2. Parallel Active Power Filter Using Fuzzy PID and Model Predictive Control under Different Operating Conditions Comparison Table for Harmonic Suppression

Total voltage distortion rate	Different working conditions	Fuzzy PID use	Model Predictive Control use	Optimization and improvement
	Cruise condition	4.46%	2.87%	1.59%
	Upgrade platform condition	4.54%	3.39%	1.15%
Maximum single harmonic value	Different working conditions	Fuzzy PID use	Model Predictive Control use	Optimization and improvement
	Cruise condition	1.76s	1.73%	0.03%
	Upgrade platform condition	1.88s	1.40%	0.48%

From the comparison table of harmonic suppression using fuzzy PID and model predictive control in parallel active power filters under different operating conditions, it can be seen that the parallel active power filters using fuzzy PID and model predictive control have significant suppression effects on harmonics under both cruising and platform raising operating conditions. The parallel active power filter with model predictive control has a better suppression effect on harmonics than the fuzzy PID active power filter. The total voltage distortion rate can be improved by 1.15% -1.19%, and the maximum single harmonic can be improved by 0.03% -0.48%. Ensure that the total voltage distortion rate under both cruising and platform lifting conditions is not more than 5%, and the maximum single harmonic does not exceed 3%, meeting the standards of China Classification Society for total harmonic distortion. The suppression effect of model predictive control is good, with lower suppression effects both in terms of total voltage distortion rate and maximum single harmonic.

5. Conclusion

Under the MATLAB/SIMULINK platform, active filter harmonic suppression measures were used to simulate the harmonic suppression of the cruise and platform up conditions of a large capacity AC integrated power system. The modeling methods and parameter design of fuzzy PID control and fuzzy model predictive control were also provided. Simulation verification was conducted on the suppression of power supply voltage distortion. By comparing the harmonic content of the bus after harmonic suppression, it can be seen that using fuzzy PID control and model predictive control for active filters can achieve good harmonic suppression effects in the case of power supply voltage distortion.

Under cruising conditions, fuzzy PID control and model predictive control active filters can suppress the total voltage distortion rate of the ship's power system by 2.13% and 3.72%, respectively, and have a suppression effect of 0.99% and 1.02% on the maximum single harmonic, respectively; Under elevated platform conditions, fuzzy PID control and model predictive control active filters can suppress the total voltage distortion rate of the ship's power system by 2.82% and 3.97%, respectively, and have suppression effects on the maximum single harmonic by 0.09% and 0.57%, respectively; Compared to the fuzzy PID control active power filter, the model predictive control active power filter has a 1.59% and 0.03% improvement in suppressing total voltage distortion rate and maximum single harmonic under cruise conditions, and a 1.15% and 0.48% improvement under elevated platform conditions; Therefore, active power filters based on model predictive control have more significant suppression effects in terms of total voltage distortion rate and maximum single harmonic.

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