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Research on Energy-saving Operation of Six-phase Induction Motor Based on Fuzzy Logic Algorithm

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Abstract

In order to further improve the energy efficiency of ships, a special tool for reducing power loss from the perspective of energy-saving operation of six-phase induction motors is proposed to achieve the purpose of reducing CO2 emissions and saving energy. For the first time, the loss separation theory and fuzzy logic algorithm are combined and optimized to build a new motor loss model, which describes the comprehensive evaluation index of power quality including frequency and voltage offset, voltage unbalance and voltage harmonics. Simulation experiments on induction motors and electric propulsion ships with different performances prove the effectiveness of the method. The evaluation results can provide an important reference for EEDI, are suitable for the formulation of power quality rules and standards, and have high practical application value in terms of ship energy efficiency and safe navigation.

Keywords

Ship; Multiphase Induction Motor; Fuzzy Logic; Power Quality; Energy Saving and Emission Reduction.

1. Introduction

As electric propulsion technology becomes more and more advanced, in the marine field, the way of using electricity instead of mechanical drive to provide power has been more widely used. Because of the rapid development of power electronic control technology, the number of motor phases becomes a free parameter. Compared with traditional three-phase induction motors, multi-phase motors have obvious advantages in occasions with high power, high current and high reliability. Therefore, research on energy-saving operation of multiphase motor systems is a hot topic at the moment.

The loss analysis of the motor itself is the most important part of its energy-saving operation. Many scholars have proposed different calculation methods. The most extensive loss calculation method is the time-step finite element method [1]. Aiming at the phenomenon that the main magnetic field changes in the iron core, Bertotti proposes a constant coefficient trinomial model based on hysteresis, eddy current and additional loss in order to refine the component loss separation.

Considering that there are a large number of power electronic loads and more complex power supply conditions in the ship's power grid, this paper extracts indicators from the perspective of power quality, combines loss separation theory with fuzzy logic algorithm [2], and proposes a way to evaluate power from the perspective of energy-saving operation of induction motors Quality tools. The comprehensive factor index is used to simulate and verify the six-phase induction motor under different experimental conditions, and the experimental results are analyzed and summarized to provide solid theoretical support for energy-saving strategies in engineering applications.

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2. Mathematical model of six-phase induction motor

The six-phase mathematical model of the six-phase induction motor is a six-dimensional system. There are many internal variables such as voltage, current, and flux linkage that are coupled with each other. It is difficult to model six-dimensional coordinates and it is difficult to use one quantity. To control the torque or speed, it is necessary to transform the multi-phase motor into a two-phase motor and some non-electromechanical energy conversion parts through a suitable coordinate transformation [3]. Equation (1) is the six-phase harmonic fundamental transformation matrix.

$$T=\sqrt{\frac{1}{3}}\begin{bmatrix} 1 & \frac{\sqrt{3}}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & -\frac{\sqrt{3}}{2} & -1 \\ 1 & -\frac{\sqrt{3}}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{\sqrt{3}}{2} & -1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \tag{1}$$

Through the transformation of the above-mentioned decoupling matrix, the original six-dimensional space vector composed of voltage and current vectors is mapped to three subspaces. These three subspaces are all two-dimensional and orthogonal to each other. The three subspaces are Z1-Z2, O1-O2 and d-q, where Z1-Z2 is the zero sequence plane, and O1-O2 is the plane that does not participate in the use of electric energy.

Under the harmonic basis, there is only the flux linkage in the d-q space. The stator flux linkage and the rotor flux linkage are interlinked, but the stator and rotor flux linkages in the Z1-Z2 and O1-O2 subspaces are not interlinked. The rotor flux The chain is related to the current transferred from the side. The flux equation of the d-q subspace in the α-β coordinate system is as follows:

$$\begin{bmatrix} \varphi_{\alpha s} \\ \varphi_{\beta s} \\ \varphi_{\alpha r} \\ \varphi_{\beta r} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{bmatrix} \tag{2}$$

During the operation of the motor, the load is driven by electromagnetic torque. The electromagnetic torque equation is as follows:

$$T_{em}=\frac{n_p}{2} I^T \frac{dL}{d\theta} I=\frac{3}{2} n_p L_{ms}(i_{\beta s} i_{\alpha r}-i_{\alpha s} i_{\beta r}) \tag{3}$$

3. Loss model based on fuzzy logic control algorithm

The loss model of induction motor in this paper is based on the combination and optimization of fuzzy logic algorithm [4] and loss separation theory. It is a new type of comprehensive power quality index and power quality evaluation method. Compared with other evaluation models, this model can better measure power quality from the perspective of energy-saving operation.

The power quality factor is directly proportional to the power loss of the induction motor under the power quality disturbance. According to the IEC/EN 60034-2-1 standard, the internal loss separation model of the induction motor can be established.

3.1 Winding loss model

The equivalent circuit of the induction motor shown in Figure 1 is nonlinear, and its resistance and reactance values depend on the current and winding temperature. Therefore, it takes into account the influence of magnetic circuit saturation and motor heating on winding resistance [5], and can analyze current under voltage and frequency deviations with high accuracy.

Current harmonics can be estimated as follows:

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$$i_h \approx \frac{u_h}{x_h} \tag{4}$$

Among them, u_h is the voltage of the h-th harmonic; x_h is the leakage reactance of the h-th harmonic.

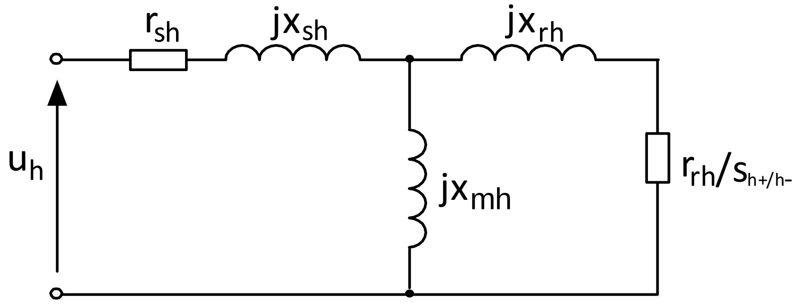

Figure 1. Harmonic equivalent circuit of induction motor

Voltage imbalance will lead to increased power loss, heat generation, vibration, and load-carrying capacity reduction of induction motors [6]. These harmful phenomena are mainly related to the negative sequence current and can be calculated by the equivalent circuit shown in Figure 2. If the magnetizing reactance is ignored, the relative negative sequence current $i\_$ can be expressed by the following formula:

$$i_{-} = \frac{u_{-}}{\sqrt{\left(r_s+\frac{r_{r-}}{s_{-}}\right)^2+(f x_s+f x_{r-})^2}} \tag{5}$$

Where $u\_$ is the negative sequence voltage component, current x_{r-} is the rotor reactance of the negative sequence current, and s is the slip of the negative sequence current:

$$s_{-} = 2 - s \approx 2 \tag{6}$$

$$r_{r-} = k_{r-} r_r \tag{7}$$

Among them, k_{r-} is the coefficient of the rotor resistance increase due to the skin effect, and the dependence in (7) can be used to predict h=1 and $s_{h\_}$=2.

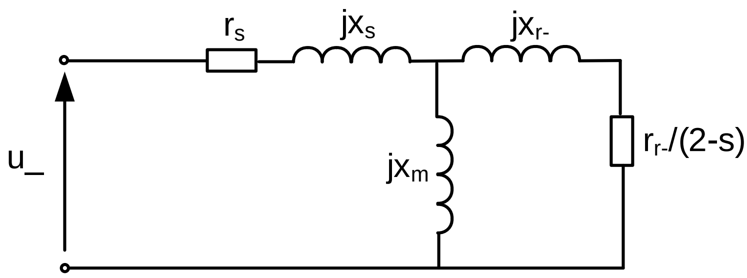

Figure 2. Negative sequence current equivalent circuit of induction motor

At the reference winding temperature, the increase in power loss in the stator and rotor windings caused by the negative sequence currents (p_{sw-} and p_{sr-}) can be estimated by the following method:

$$p_{sw-} = i_{-}^2 \tag{8}$$

$$p_{wr-} = \frac{1}{i_{rref}^2} k_{r-} i_{-}^2 \tag{9}$$

3.2 Iron loss model

The power loss in the iron core can be divided into hysteresis loss, typical loss and excess loss [7]. However, in order to simplify the analysis, the typical loss and excess loss can be regarded as eddy current loss together.

Under the distorted power supply voltage, the power loss of the iron core can be evaluated as follows:

$$p_{Fe} = k_{Fedist} p_{Fesin} \tag{10}$$

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Among them, k_{Fedist} is the coefficient of increase in core power loss caused by voltage waveform distortion, which is calculated as follows:

$$k_{Fedist} = \eta_B^x p_h + \chi^2 p_h \tag{11}$$

In the formula, χ is the voltage ratio. η_B is the ratio of the magnetic flux of the sinusoidal power supply to the peak distortion voltage.

3.3 Mechanical loss model

The mechanical losses in induction motors are caused by friction and wind resistance of the bearings. These losses can be recalculated as proportional to the square of the speed [8]. In this study, it is assumed that the relative mechanical loss p_m is:

$$p_m = t_{par} \tag{12}$$

Among them, t_{par} is the relative value of parabolic load torque.

3.4 Stray loss model

Stray loss is caused by space harmonics such as gap leakage flux, slot leakage flux and floating leakage flux. These losses are related to the complex geometry of the motor, mostly related to the presence of teeth and slots. Stray loss is divided into no-load loss and load stray loss.

In this study, the no-load stray loss is included in the iron loss. For voltage and frequency deviations in the ship's power system, this simplification should not lead to large errors. Load stray loss includes many components, such as stator slot eddy current loss, rotor suspended eddy current loss, rotor slot MMF-stator tooth pulsation loss, etc. [9], these losses are usually eddy current in nature. The prominent load stray loss components are generally calculated in proportion to the square of the stator current. In addition, some stray load loss components are proportional to the speed. In this study, the load stray loss is recalculated as:

$$p_{sll} = i_{s1}^2 t_{par}^{0.9} \tag{13}$$

Among them, t_{par} is the relative value of parabolic load torque.

3.5 Power quality factor model

Because the mathematical description of the loss separation model is inconvenient to analyze in power quality, a comprehensive index needs to be formulated to approximate the motor loss caused by power quality disturbances [10]. For the sake of simplicity, the approximate value applied is based on the sum of the power loss caused by each power quality disturbance:

$$p_{tot} = c_{veq} = p_{fund} + p_{har} + p_{unbal} \tag{14}$$

Among them, p_{fund} represents the relative power loss caused by the fundamental voltage, p_{har} represents the relative power loss caused by voltage harmonics, and p_{unbal} represents the relative power loss caused by voltage imbalance.

4. Simulation

In order to verify the effectiveness of power quality factor monitoring of motor power loss and efficiency evaluation, a direct torque control induction motor model was established with MATLAB/Simulink, and a computer-based power quality analyzer was used to monitor various indicators of electrical quantities. The monitoring device block diagram is shown in the figure 3 shown. Compare the power loss calculated by the model (P_{calc}) with the measured value (P_{meas}). In addition, check the power loss P_{meas} with the factor c_{veq} value.

Using the above experimental parameters and power loss model, the power quality factor cveq value corresponding to each situation can be obtained. For each power quality disturbance situation considered, the power loss Pmeas of at least one motor corresponds to the factor cveq[11], As shown in Table 1. The only exceptions are voltage harmonics and voltage waveform distortion (cases 16 and 17). In these cases, the power loss corresponding to the cveq value is significantly greater than that

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of Pmeas. This is because the increase in power loss caused by voltage imbalance and voltage waveform distortion is very sensitive to motor parameters, especially the value of short-circuit reactance. In practical applications, it can be considered that the increase in power loss is approximately inversely proportional to the square of the short-circuit reactance.

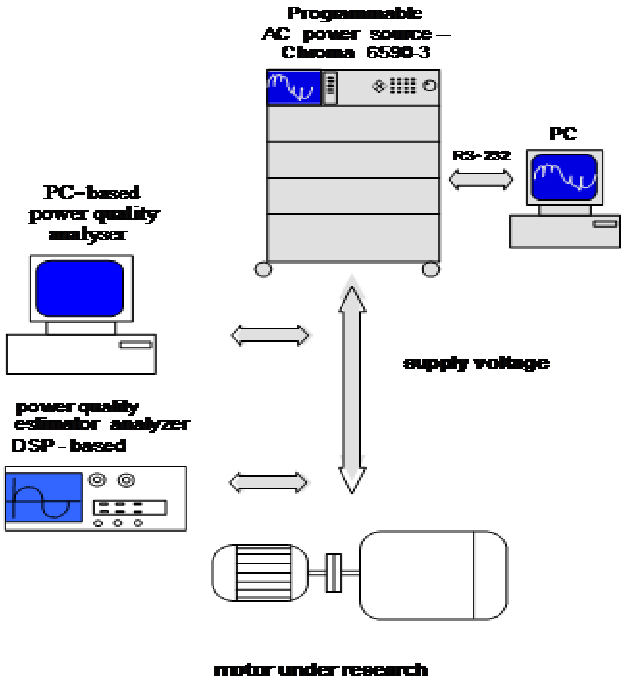

Figure 3. Monitoring device configuration diagram

Table 1. The power quality factor cveq value in given conditions

condition	Power quality disturbance	cveq
1-2	f=95% frat, U=106% Urat	1.43
3-4	f=95% frat	1.108
5-6	U=106% Urat	1.132
7-9	f=105% frat, U=90% Urat	1.359
10-12	f=105% frat	1.269
13-15	U=90% Urat	1.093
16	u5=9.2% Urat	1.114
17	u-=3% Urat	1.112

Based on the above analysis and calculation data, a more intuitive waveform diagram is drawn, as shown in Figure 4.

Then take the practical ship as the object, conduct investigation and research on the dynamic positioning (DP) ship of the Maritime University of Gdynia. The selected object is a typical electric propulsion ship. In this paper, electric propulsion is used in rough sea conditions. . During the study, the two propulsion units were operated by Active Front End Power Drivers (AFE), each rated at 300 kW. The rated voltage of the power system is 400V, and the rated frequency is 50HZ. During the study period, two diesel generators were operated in parallel with rated powers of 425KVA and 200KVA.

During the 26-minute sea voyage, the forward speed of the ship is shown in Figure 5 due to the gradual increase in driving load. Figure 6 shows the corresponding active power when two generators are running in parallel. A slight change in speed was observed after 17 minutes, which was caused by

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the change of the ship's heading and the increase in hydrodynamic drag. Secondly, it can be noticed that during the research process, due to the work of auxiliary power electronic equipment, a certain regular load change occurred. Therefore, the increase in speed will cause irregular changes in power. Finally, the change in active power causes a stepped drop in frequency, which is about 0.35Hz. Therefore, as shown in Figure 7, such a small frequency change is clearly visible.

Finally, the c_{veq} value is not constant, but changes as shown in Figure 8. The calculations before and after the growth rate are the average of c_{veq}, the low speed is 1.038, and the medium speed is 1.012. Obviously, the decrease in the power quality factor value is related to the decrease in frequency, and the voltage imbalance has a slight increase from 1.3% to 1.9%. In short, the c_{veq} factor is mainly affected by frequency changes.

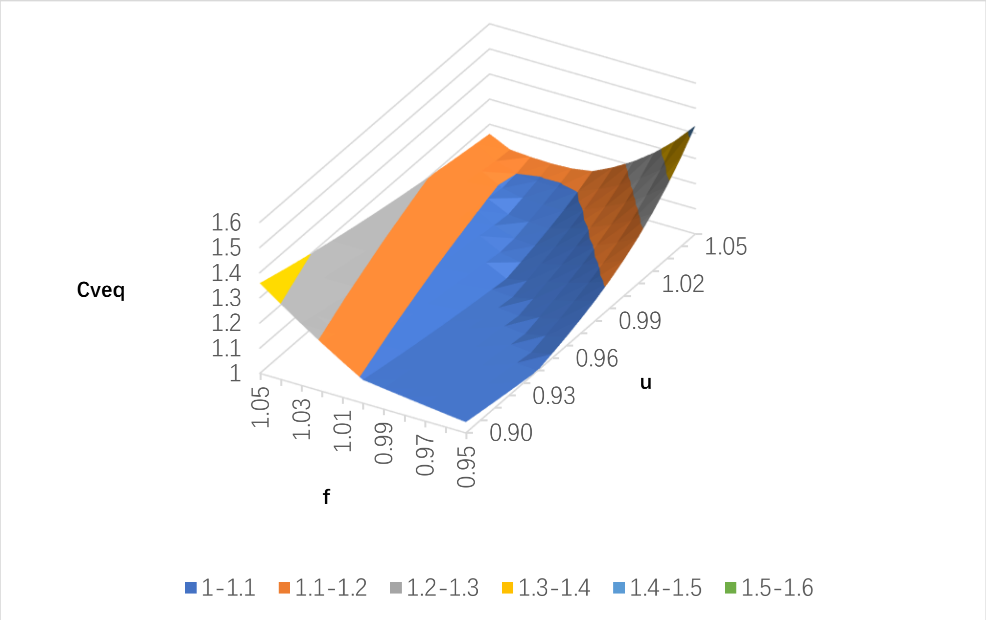

Figure 4. Power quality factor and voltage, frequency relationship diagram

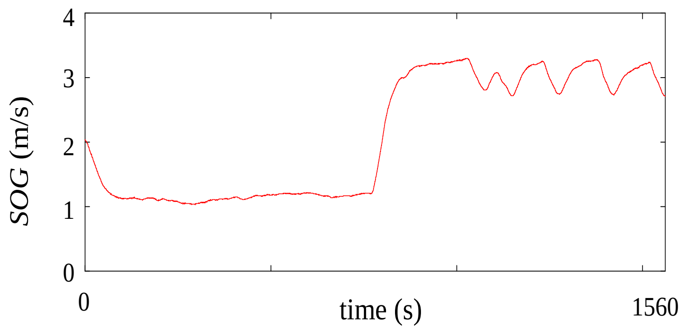

Figure 5. The speed of the DP ship relative to the ground

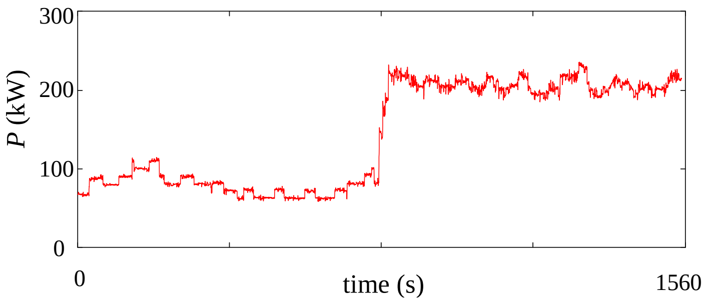

Figure 6. Active power when two generators of DP ship are operated in parallel

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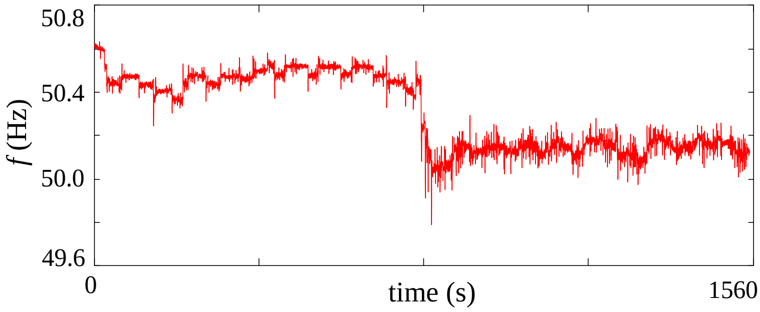

Figure 7. Frequency change of DP ship in increasing load

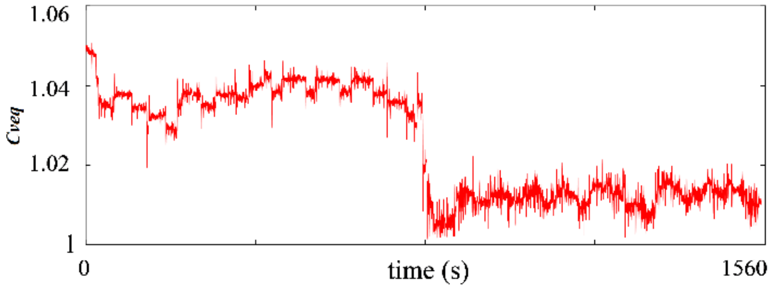

Figure 8. The change of cveq when the DP ship speeds up gradually in wind and waves

It can be seen that the main influencing factor for the energy-saving operation of the six-phase motor of the marine propulsion system is frequency. During operation, the value of c_{veq} will reach 1.14, resulting in reduced energy efficiency and aging of electrical equipment. Therefore, considering the motor characteristics and operating efficiency from the perspective of power quality has more intuitive results. From the perspective of energy-saving operation of induction motors, this research requires power quality monitoring. The proposed power quality factor model is a very suitable tool for evaluating power system power quality.

5. Conclusion

This paper starts from the mechanism of fuzzy logic algorithm and loss separation model, pays attention to a new perspective of energy-saving operation of motors, and monitors the power quality of the ship's power grid. Strict power quality monitoring on ships is more helpful to reduce energy loss, so a special tool, namely the power quality factor c_{veq}, is proposed. This coefficient has physical meaning and has been mathematically deduced and verified by experiments. This value is proportional to the power loss of the induction motor caused by the power quality interference. The c_{veq} close to 1 indicates that the power quality disturbance has little effect on the loss of the induction motor. The power quality factor is a comprehensive manifestation of frequency and voltage deviation, harmonic content and voltage unbalance. This coefficient has been simplified by the mathematical model, which is convenient for use in engineering practice. Taking the electric propulsion ship as an example, the disturbance environment of the ship's power grid is provided by the interference of wind and waves and the digital simulation of various indicators is carried out. The experiment verifies the effectiveness of the power quality factor model for the evaluation of the energy-saving operation of the motor. c_{veq} also provides important supplementary instructions for EEDI (Energy Efficiency Design Index), which bridges the gap in the existing technology for evaluating power quality from the perspective of energy-saving operation of induction motors. According to IEC and IEEE standards to analyze power consumption, the standard proposed in this article is: the maximum value c_{veq} = 1.2, and the recommended value c_{veq} = 1.05. The energy efficiency evaluation model proposed in this paper is simple, the parameters have clear physical meanings, the standards are easy to implement, and have rigorous theoretical analysis and practical proofs. The model will provide a safe and reliable

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reference standard for ship power system development and design and internal system integration. Improve the energy efficiency and safety performance of ships.

References

[1] H.C. Zhao, D.D. Zhang, Y.L. Wang, et al. Time-stepping finite element analysis of no-load iron loss distribution of asynchronous motor [J]. Chinese Society for Electrical Engineering, 2016, 30(30): 99-106.

[2] H.Y. Guo, J.S. Liu and H.Z. Chen: Comprehensive evaluation of distributed power network based on fuzzy mathematics and combined weighting method [J]. Modern power, 2017, 34(2): 14-19.

[3] W.X. Song, S.K. Yue, X.X. Wu, et al. An Improved Model Predictive Direct Torque Control Method of Asynchronous Motor [J]. Journal of Shanghai University (Natural Science Edition), 2018, 24(6): 861-876.

[4] H.W. Hu. Realization of Fuzzy Control Theory in Frequency Conversion Speed Regulation System [J]. Electrotechnical, 2017(5): 47-50.

[5] Terriche Y., Mutarraf M.U., Golestan S., SuC.L., Guerrero J.M., Vasquez J.C., Kerdoun D., “A hybrid compensator configuration for VAR control and harmonic suppression in all-electric shipboard power systems”, IEEE Transactions on Power Delivery,Vol.35,No 3,(2020),pp 1379-1389.

[6] Donolo P., Pezzani C., Bossio G., De Angelo C., Donolo M, “Derating of induction motors due to power quality issues considering the motor efficiency class”, IEEE Transactions on Industry Applications, Vol.56, No.2, (2020), pp 961-969.

[7] Mohamed Zaky; Mohamed Metwaly.Sensorless Torque/Speed Control of Induction Motor Drives at Zero and Low Frequency with Stator and Rotor Resistance Estimation[J]. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2016, (99): 1-1.

[8] Aciego, Juan.J., Gonzalez Prieto,Ignacio,etc. Modsl Predictive Control of SixPhase Induction Motor Drives Using Two Virtual Voltage Vectors[J]. IEEE Journal of Emerging and Selected Topics in Power Electrnoics, MAR 2019(07): 321-330.

[9] Kumar D., Zare F., “Comprehensive review of maritime microgrids: system arvhitectures, energy efficiency, power quality and regulations”, IEEE Access, Vol.7, No.99, (2019), pp 1-11.

[10] K.Y. Liu, W.X. Sheng, M.Y. Qin, et al. Power Quality Analysis Method of Active Distribution Network Considering Multiple Disturbance Sources [J]. Power grid technology, 2020, 44(6): 2303-2309.

[11] [11] Q.Y. Zeng, H.G. Yang and X.P. Yang: Comprehensive evaluation of power quality considering index relevance [J]. Journal of Electric Power System and Automation, 2016. 28(7): 73-78.