

# Optimization of asynchronous motor with Taguchi method based on Finite Element Analysis

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**Abstract.** In order to study the operation process of the motor and improve the operating performance of the motor, this paper performs finite element simulation of the three-phase asynchronous motor and optimizes the initial design by using the Taguchi method. Firstly, a three-phase asynchronous motor model is established with the voltage, current, torque, flux linkage, distribution of the flux lines and magnetic induction intensity of the motor under rated conditions is verified by Finite Element Analysis (FEA), and the total accuracy reaches 92%. Then, the parametric simulation of the stator and rotor cogging parameters and stator and rotor parameters is carried and the sensibility of different parameters on the motor torque is obtained. The rotor cogging parameter Hs01 and stator cogging parameter Hs0 had the highest sensitivity, which were 75% and 16%, respectively. Finally, the Taguchi method was applied to optimize the torque of the motor, and the torque was increased by 9.5%.

## 1. Introduction

Energy is a significant material foundation and driving force for the progress of human civilization, which is related to the national economy and people's livelihood and national security. At present, the following national energy demand and the wide application of motors in equipment manufacturing, national defense, industrial production and daily life in the new era, and with the rapid growth of the demand for high-performance motors, how to carry out efficient motor simulation analysis and optimization design is particularly important.

Traditional motor optimization is mainly carried out by parameter sweeping method, a limited number of optimization variables are analyzed by grid analysis of distance length, and the most suitable candidate design is artificially selected. However, this method is inefficient and difficult to obtain the optimal solution. With the development of optimization algorithms and modeling technology, motor design has been able to achieve its functional requirements through model combined with optimization goals, and achieve goals such as reducing costs, reducing losses, and improving efficiency.

In the simulation and optimization design of motors, scholars at home and abroad have done a lot of research. Literature [1] The preliminary design scheme of the motor is obtained by the magnetic circuit method, and the electromagnetic field analysis of the motor is analyzed by the finite element method to verify the rationality of the scheme, and then the permanent magnet inclined pole is used and the design parameters of the motor are optimized by combining genetic algorithm. Literature [2] Firstly, the development status of high-speed motors is analyzed, and the structure and design characteristics of different types

of high-speed motors are summarized, the stator and rotor design are analyzed in detail according to the motor indicators, and the protection measures for the loss of motor operation are considered by analyzing the number of stator poles, grooves, core materials, stator windings, rotor geometry, rotor copper bar materials and other parameters. The literature [3] summarizes the research work carried out by domestic and foreign scholars in the rotor pole optimization technology of permanent magnet synchronous motor in recent years, classifies different rotor pole optimization technologies, compares their advantages and disadvantages. The literature [4] uses the finite element method to simulate the operation of the motor, and introduces different numerical techniques for calculating inductance and magnetic force based on the three axisymmetric open boundary problems, so as to better explain and analyze the phenomena of magnetic saturation and magnetized magnetic inductance. Paper [5] Based on the motor parameters, a numerical model considering the magneto strictive effect of silicon steel sheet is established, and the Multiphysics coupled vibration analysis is carried out. Literature [6] uses finite element analysis to evaluate the influence of rotor and stator diameter, tooth width and number of windings on the optimal design of motors, and studies the feasibility of magneto resistive network limiting the parameter domain of finite element simulation, and finally performs experimental verification. Paper [7] analyzes the sensitivity analysis of the performance index of the rotor geometric parameters of permanent magnet synchronous reluctance motor, including inductance difference, torque, torque ripple and permanent magnet flux linkage. The sensitivity of performance indicators to geometric

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parameters such as flux barrier angle, width, length and position is obtained experimentally. However, there are still additions to the above literature for the study of variables for specific motor parameters. However, there are still more related study about the optimization of motor besides above . In this paper, the finite element simulation and optimization design of three-phase asynchronous motor will be promoted to analyze the sensitivity of motor parameters and optimize the experimental design, and the influence of cogging parameters, stator parameters and rotor parameters on the working performance of three-phase asynchronous motor will be explored and optimized.

## 2. Simulation analysis of three-phase asynchronous motor

This paper will take the three-phase asynchronous motor as the research object, and use MAXWELL software to do the simulation analysis. Figure 1 is the structure diagram of the three-phase asynchronous motor, and the basic parameters are shown in Table 1.

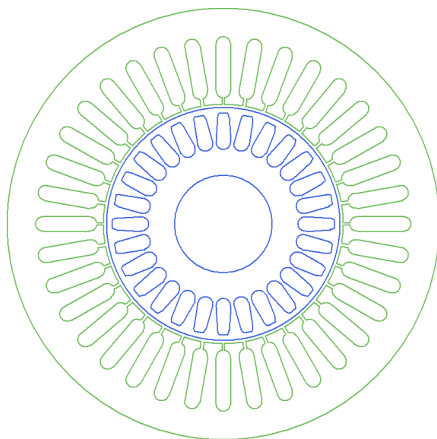


Figure 1. Schematic diagram of three-phase asynchronous motor

Table 1. Basic parameters of the motor

Parameter	Value
Rated power/W	1100
Rated voltage/V	380
Rated speed/rpm	1450
Rated operating temperature/°C	75
Stator outer diameter/mm	140
Stator inner diameter/mm	78
Axial length/mm	250
Core material	Style D21_50
Number of stator slots	36
Rotor outer diameter/mm	76
Rotor inner diameter/mm	32
Roter material	Style D21_50
Rotor guide strips	Style copper

Through the parametric simulation in software, we obtain some parameter images of the motor in the rated operating

state, as shown in Figure2, Figure3, Figure4, Figure5, Figure6, Figure7.

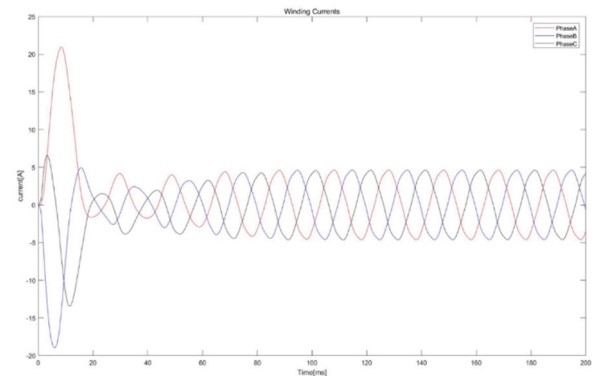


Figure 2. Asynchronous motor simulation of Current

As above figure, the maximum current value reaches 20.96A when the current is in the transient state, which is 4.6 times that of the steady state . Steady state is reached at 24ms, and then it changes in a sinusoidal curve. The rms value is 3.23A, which is 0.34A different from the rated parameters, and the simulation accuracy is 88.4%. According to the above conclusions, it can be obtained that the motor simulation results have high accuracy and meet the design requirements.

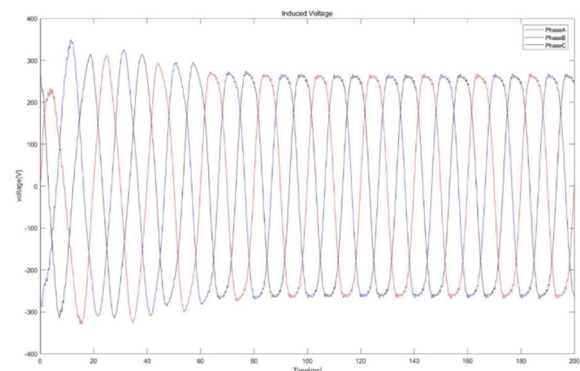


Figure 3. Asynchronous motor simulation of load Voltage

From the above figure, the three-phase voltage waveform is symmetrical, the maximum value is 350.1V, the error from the rated value is 30V, and the simulation accuracy is 92.1%, which meets the simulation accuracy requirements. After reaching the steady-state process in 60ms, the magnetic flux is partially saturated, the voltage is approximately a sine wave change, and the waveform distortion is small.

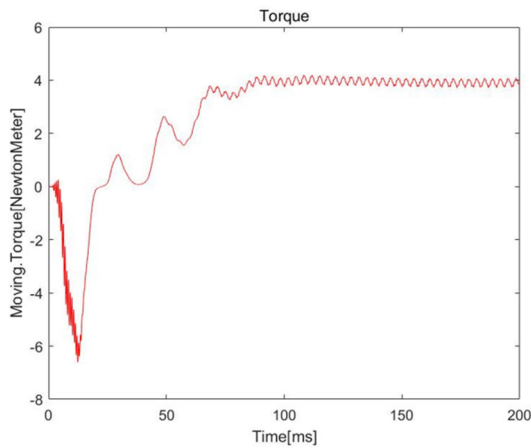


Figure 4. Simulation of Torque

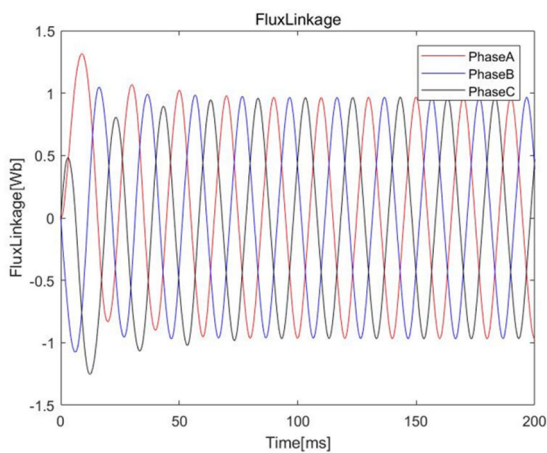


Figure 5. Simulation of FluxLinkage

With the rotation of the motor, the motor reaches a steady state after undergoing a transient process of 90ms, the average value is 4.01Nm, the torque fluctuates in the range of 3.88-4.14, the fluctuation range is 3.14%, and the torque fluctuation is small.

And from the above figure5, it can be seen that the waveform of the flux link has a three-symmetry relationship, the maximum value is 1.31Wb, and after reaching the steady-state process in 60ms, the maximum value of the flux link is stable at 0.95Wb.

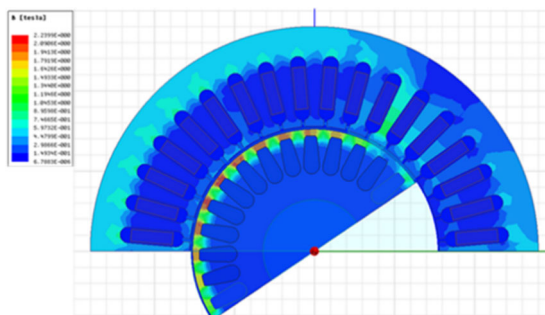


Figure 6. Simulation of Magnetic Density

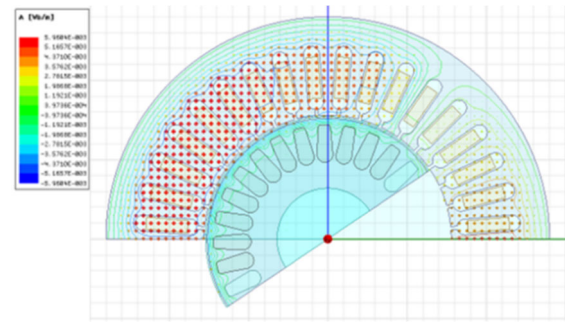


Figure 7. Simulation of Magnetic Induction

As can be seen from the above figure6, the maximum magnetic density of the stator part is 1.74 tesla, which appears in the tooth, and it is necessary to protect and monitor the force condition and thermal condition of the tooth during the operation of the stator. The maximum value of the magnetic density of the rotor part is 3.13tesla, which appears in the rotor tooth at the junction of the stator and rotor, which is located at the junction of the rotor guide bar and the stator copper wire, so the magnetic density is large. The above magnetic density phenomenon is in line with reality and meets the design requirements. As can be seen from the above figure7, the magnetic induction line closure is small, so the magnetic leakage phenomenon of the motor is relatively small, which meets the design requirements.

### 3. Finite element simulation of three-phase asynchronous motor

In order to explore the influence of motor parameter changes on motor performance, four parameters of stator, rotor cogging, stator and rotor are selected as independent variables for modification, and finite element simulation is carried out. The change in motor performance is measured using motor torque as a dependent variable, and the results obtained are as follows.

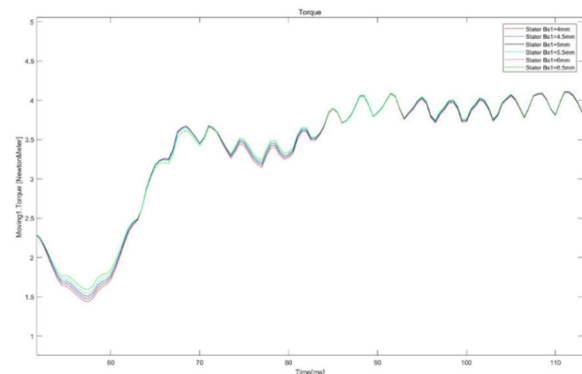


Figure 8. Stator Parametric Simulation

As can be seen from Figure 8, it can obtain that the parameter range of modified stator Bs1 is 4mm~6mm, and its rated parameter is 5mm. When the parameter is smaller, the smaller the torque average, when the parameter increases, the torque average value also increases.

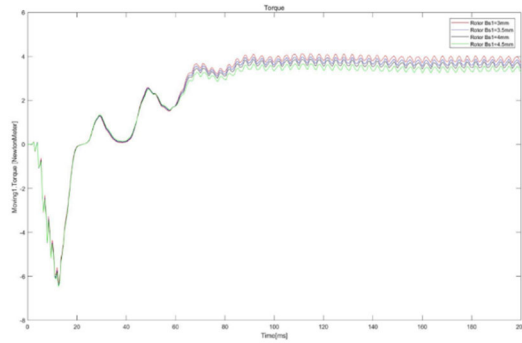


Figure 9. Rotor Parametric Simulation

As can be seen from Figure 9, it can obtain that the parameter range of modified rotor Bs1 is 3mm~4.5mm, and its rated parameter is 4mm. When the parameter is smaller, the larger the torque average, when the parameter increases, the torque average value also decreases.

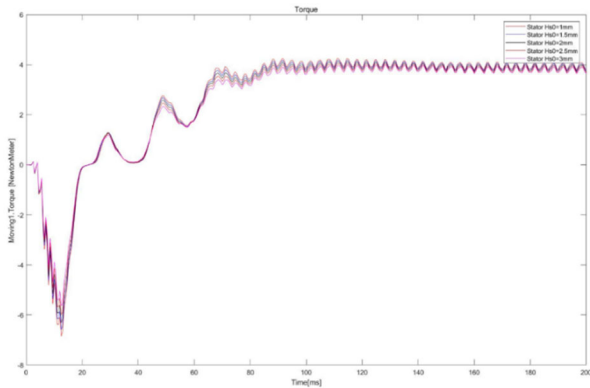


Figure 10. Stator Cogging Parametric Simulation

From Figure 10, it can be obtained that the parameter range of modified stator cogging Hs0 is 1mm~3mm, and its rated parameter is 2mm. When the parameter is smaller, the average torque is larger, and when the parameter increases, the average torque value also decreases.

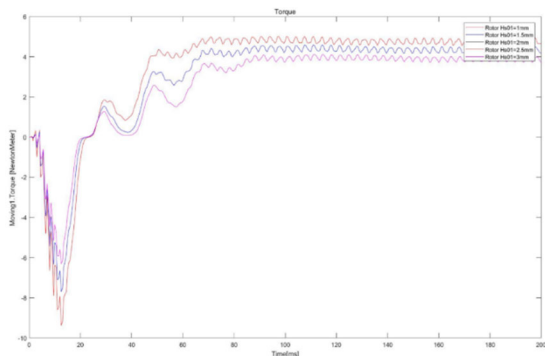


Figure 11. Rotor Cogging Parametric Simulation

From Figure 11, it can be obtained that the parameter range of modifying the rotor cogging Hs01 is 1mm~3mm, and its rated parameter is 2mm. When the parameter is smaller, the average torque is larger, and when the parameter increases, the torque average decreases. There are cases where the torque curves coincide when the parameters change little.

#### 4. Optimized design of three-phase asynchronous motor based on Taguchi method

The Taguchi method was proposed by Dr. Taguchi Genichi in 1952 to find the best combination of parameters to improve product quality, Taguchi method has been rapidly promoted and applied in Japan, achieving huge economic benefits and social impact, so that the method began to be valued and applied by the global industry. The design flowchart of Taguchi's optimization design method is shown in Figure 12.

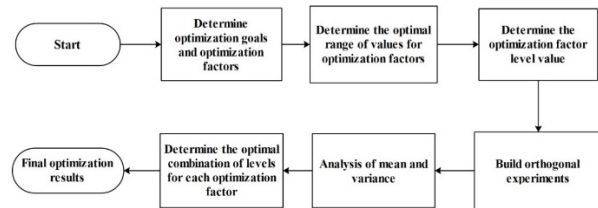


Figure 12. Taguchi method optimization design flowchart

According to the motor design requirements, the stability value of torque should be as high as possible, so the torque  $T_e$  is selected as the optimization goal, because the motor cogging, stator and rotor have a great influence on the performance and operation of the motor, so this paper selects the stator cogging Hs0, rotor cogging Hs01, stator core inner diameter Bs1 and these four parameter variables are selected as optimization factors.

Maxwell software is used to repeatedly adjust and simulate the optimization factor parameters to obtain the optimal value range, and the value range of each optimization factor is shown in the table. Five influence levels were selected equidistant in the optimal range of each factor, and the five level values were named as level values 1, 2, 3, 4 and 5 according to the principle of order from smallest to largest, and the values of each level were shown in the table 2.

Table 2. The number of optimization factor levels

Optimization factor	LEVE L1	LEVE L2	LEV EL3	LEVE L4	LEVE L5
Stator cogging Hs0/mm	1	1.5	2	2.5	3
Rotor cogging Hs01/mm	1	1.5	2	2.5	3
Stator inner diameter Bs1/mm	4	4.5	5	5.5	6
Rotor inner diameter Bs1/mm	3	3.5	4	4.5	5

According to the four optimization factors (variables) selected in Table 2 and Table 3 and the five horizontal values determined by each optimization factor, the  $L_{16}(4^5)$  orthogonal table was established by using the construction principle of orthogonal table and the

experimental design principle of Taguchi's algorithm, and a multivariate optimization design can be realized in only 25 experiments, which greatly reduces the degree of calculation and the number of experiments. The finite element method was used to establish 25 motor models, and the parametric simulation analysis was carried out by Maxwell software, and the results of the finite element solution were shown in Table 3.

Table 3. Finite element solution results

Test Number	Experimental Matrix				T/Nm
	Hs0	Hs01	Bs1	Bs1	
1	1	1	1	1	4.872
2	1	2	3	4	4.456
3	1	3	5	2	4.079
4	1	4	2	5	3.903
5	1	5	4	3	4.069
6	2	1	5	4	4.795
7	2	2	2	2	4.417
8	2	3	4	5	3.874
9	2	4	1	3	4.069
10	2	5	3	1	4.005
11	3	1	4	2	4.712
12	3	2	1	5	4.301
13	3	3	3	3	3.974
14	3	4	1	5	3.986
15	3	5	2	4	4.008
16	4	1	3	5	4.582
17	4	2	5	3	4.349
18	4	3	2	1	4.174
19	4	4	4	4	4.483
20	4	5	1	2	4.263
21	5	1	2	3	4.029
22	5	2	4	1	3.979
23	5	3	1	4	3.846
24	5	4	3	2	3.892
25	5	5	5	5	3.750

The statistical analysis of experimental data is carried out from the orthogonal experimental table and finite element analysis results, and in order to obtain the proportion of the influence of all optimization factors on the optimization goal, the average analysis and variance analysis are carried out below.

Firstly, the average value of the finite element simulation results of the optimization target is calculated according to Equation (1) as follows:

$$m = \frac{1}{n} \sum_{i=1}^n S_i \quad (1)$$

Where m is the mean of the experiment; n is the number of experiments;  $S_i$  is the  $i$ th optimization target value. Obtain  $m=4.195$  Nm.

Then, the average value of the simulation analysis of the motor torque performance index corresponding to the change of each optimization factor is analyzed, and the average value of the optimization factor at different levels is first analyzed. According to Equation (2), the average calculation result of torque T is shown in Table 4 when all optimization factors are taken at different levels.

$$m(\eta) = \frac{1}{5} (\eta(1) + \eta(2) + \eta(3) + \eta(4) + \eta(5)) \quad (2)$$

Table 4. Average value of motor indicators at different levels of various optimization factors

Optimization factor	LEVEL	T/Nm
Stator cogging Hs0	1	4.2758
	2	4.232
	3	4.1962
	4	4.3702
	5	3.8272
Rotor cogging Hs01	1	4.598
	2	4.3004
	3	3.9894
	4	4.0048
	5	4.019
Stator inner diameter Bs1	1	4.223
	2	4.1062
	3	4.1818
	4	4.2234
	5	4.2433
Rotor inner diameter Bs1	1	4.2575
	2	4.2726
	3	4.098
	4	4.3176
	5	4.066

From Table 5, the motor optimization factors that can make the highest motor torque are stator cogging Hs0(4), rotor cogging Hs01(1), stator core inner diameter Bs1(5), rotor core inner diameter Bs1(4), respectively, 4.3702, 4.598, 4.2433, 4.3176.

According to the average table of optimization targets analyzed above and the average table of motor performance indicators of various optimization factors at different levels, the variance (SS) of optimization factors under motor torque performance indicators and the proportion of their influence on motor performance can be calculated from equation (3). The calculation results are shown in Table 5.

$$SS = \frac{1}{n} \sum_{i=1}^n (m_{xi}(S) - m(S))^2 \quad (3)$$

Where X is each optimization factor (optimization parameter); S is the optimization goal;  $m(S)$  is the average of the optimization target;  $m_{xi}(S)$  is the average of an optimization target for factor X at level i; SS is the variance value under the motor optimization factor X, and n is the level value of each optimization factor.

Table 5. The influence of each optimization factor on the torque of the motor

Optimization Factor	T/Nm	
	SS	Specific Gravity
Stator cogging Hs0	0.042	16%
Rotor cogging Hs01	0.197	75%
Stator inner diameter Bs1	0.006	2%
Rotor inner diameter Bs1	0.017	7%

From Table 5, it can be obtained that the rotor and stator cogging parameters have a relatively large influence on the operating performance of the motor, and the total influence is 91%.

## 5. Conclusion

In this paper, finite element simulation is carried out for three-phase asynchronous motor, and the optimized design is carried out by the Taguchi method. Firstly, a three-phase asynchronous motor model is established to study the parameters of motor operation under normal conditions, and the total simulation accuracy reaches 92%. Then, the parameters of cogging, stator and rotor are modified for parametric simulation, and the influence of different parameters on the motor torque is obtained. Finally, the Taguchi method was applied to optimize the torque design of the motor, and the torque was increased from 4.01Nm to 4.39Nm, which was increased by 9.5%, and the rotor cogging Hs01 and stator cogging Hs0 had the highest sensitivity, 75% and 16%, respectively.

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