Design and Analysis of Permanent Magnet AC Servo Motor Based on ANSYS

Hongdan Lei\textsuperscript{a}, Ying Chen\textsuperscript{1}, Dongdong Chen\textsuperscript{1}, Zongwei Li\textsuperscript{1}, Hongguan Zhu\textsuperscript{1}.
\textsuperscript{1}Department of Automation, Wuhan University of Technology, Wuhan, Hubei, China
\textsuperscript{*}e-mail: lhd253986@whut.edu.cn

Abstract. According to the design requirements, this paper studies electromagnetic design theory, establishes calculation model to determine a design scheme of permanent magnet AC servo motor, and uses finite-element simulation to analyze it under no-load and load conditions. The results show that the design parameters and output performance of the motor can well meet the technical specifications, which can provide a reference for further study.

1. Introduction
With the development of modern control technology, servo motor and its control system are widely used in various fields of industry\cite{1}. The permanent magnet AC servo motor has good low-speed performance, fast dynamic response, small moment of inertia and high torque current ratio, which can well meet the requirements of high-performance servo drives. Therefore, it has been favored by many researchers and developers, and has become the mainstream of AC servo system\cite{2}.

In this paper, in order to give a design scheme of the permanent magnet AC servo motor, the electromagnetic design is deeply studied, and the appropriate motor sizes and parameters are selected and optimized according to the calculation model. And the rationality of the motor design is verified based on the finite-element simulation, which lays the foundation for the prototype development and further research.

2. Electromagnetic design
2.1. Requirements of design
According to the requirements of the actual project, a 750W permanent magnet servo motor with rated speed of 3000rpm is designed. The main technical specifications are shown in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
Rated power & 750W \\
Rated voltage & 220V \\
Rated speed & 3000rpm \\
Efficiency & >90\% \\
Stator outer diameter & <80mm \\
\hline
\end{tabular}
\caption{Main technical specifications}
\end{table}

2.2. Main sizes and parameters
The main sizes of permanent magnet servo motor depend on the required maximum torque and dynamic response index\cite{3-4}. The relationship between the main sizes, electromagnetic load and maximum torque is as follows:

\[ D_{il}^2 L_{ef} = \frac{4T_{\text{max}} \times 10^4}{\sqrt{2\pi} B_{e1} A} \]  \hspace{1cm} (1)

Where, \( T_{\text{en}} \) is the required maximum torque; \( B_{e1} \) is the amplitude of fundamental wave of air gap flux density, or the magnetic load; \( A \) is the electrical load; \( D_{il} \) is the inner diameter of stator; \( L_{ef} \) is the effective length of the motor core.

When the dynamic response index is reflected in the maximum electromagnetic torque, the motor is required to accelerate from static to basic speed \( \omega_b \) in time \( t \), and the inner diameter of stator must meet the following requirements:

\[ D_{il} = \left( \frac{8\sqrt{2} p t B_{e1} A}{\omega_b \rho_{Fe} \times 10^3} \right)^{1/2} \]  \hspace{1cm} (2)

In the formula(2): \( p \) is the number of poles and \( \rho_{Fe} \) is the density of rotor core material. If the rated parameters have been determined, the main sizes depend on the electromagnetic load, which includes \( A \) and \( B_{e1} \). When the electromagnetic load is higher, the motor sizes and weight are smaller, and the materials is less used. And if the magnetic load is greater, the motor core will be saturated more easily; while the electrical load is greater, the temperature rise will be higher\cite{5}. Therefore, electromagnetic load should be selected reasonably.

Also, it is necessary to select the appropriate length diameter ratio of the motor. Considering electromagnetic load and saturation of magnetic steel, the appropriate length diameter ratio \( \lambda \) also has a certain relationship with operating performance and processability, which can be expressed as follows:

\[ \lambda = \frac{L_{ef}}{D_{il}} \]  \hspace{1cm} (3)

The length of air gap is also an important parameter. In general, the air gap field of permanent magnet motor is generally larger than that of induction motor of the same specification, which can effectively reduce the stray loss and improve vibration and noise\cite{6}. And the air gap length of internal permanent magnet motor is generally smaller than that of surface mounted permanent magnet motor, because of the larger speed range of constant power operation. If too large, the direct axis inductance will be small and the flux weakening ability will be insufficient.

2.3. Design scheme

The results of design sizes and parameters can be seen in Table 2.

| Table 2. Motor design scheme |
|-----------------------------|
| **Parameter**               | **Value(mm)** |
| Stator outer diameter       | 75            |
| Stator inner diameter       | 46            |
| Air gap length              | 1.5           |
| Rotor inner diameter        | 19            |
| Core length                 | 60            |
| Permanent magnet thickness  | 3.04          |

In this paper, 8-pole/18-slot matching scheme is used, while the semi-closed pear-shaped slots with parallel teeth and surface mounting structure of rotor permanent magnet are adopted. And DW310_35 silicon steel is adopted as the stator and rotor material; while a kind of SmCo magnetic steel XG196/96 is used as the permanent magnet material, the remanence and coercivity of which reaches 0.96 T and
690 kA/m respectively.

The design process can be seen in Figure 1. The process of designing approximated by calculation to give an initial value, and it will be optimized with the help of simulation. Iteration is done to be able to find the optimal design in accordance with the desired design.

3. Finite-Element simulation analysis

3.1. Finite-Element method

The Finite-Element(FE) method discretizes the whole solution region and divides the large areas into many small sub regions, namely "element" or "finite element"; then, applies the principle of solving boundary problem to these sub regions to solve each small region, and added up the calculation results of each small region to obtain the solution of the whole region[7].

Based on the design scheme, a FE model is built on ANSYS, and the FE simulation analysis is carried out under no-load and load conditions to verify whether the back EMF coefficient, cogging torque and no-load flux density are reasonable, and the load performance of the motor is analyzed.

3.2. No-load simulation analysis

In the no-load state, the distribution of no-load magnetic line and magnetic flux density is shown in figure 2 and figure 3 through post-processing, and the no-load back EMF, air gap radial flux density distribution and cogging torque are obtained.
It can be seen that the magnetic lines are evenly and symmetrically distributed in stator core, permanent magnet and air gap of the motor, and there is no magnetic lines in stator slot, which indicates that there is almost no magnetic flux leakage. The distribution and amplitude of magnetic flux density is reasonable, and the magnetic circuit structure is rational, which is conducive to reduce the iron loss and improve the efficiency.

As shown in Figure 4, although the no-load Back EMF contains a certain harmonic component, the sinusoidal degree is good, which can verify the rationality of the winding design. The harmonic component is mainly due to the slots, which will cause non-uniform magnetic conductivity and induce tooth harmonic electromotive force[8]. The cogging torque fluctuation at 360 mechanical angle is shown in Figure 5, and the maximum amplitude is 14.43mN·m (about 0.61% of the rated torque), which has little influence on the starting and operation performance.

The air gap magnetic field is generated by permanent magnet under no-load condition. Figure 6(a) shows the radial flux density of no-load air gap. The waveform tends to be sinusoidal generally, but there are some burr and concave convex due to the influence of stator teeth. In order to see the harmonic
distortion of the air gap magnetic field more clearly, Figure 6(b) is obtained by Fourier analysis. It can be seen that the amplitude of fundamental wave is 0.85T, and the main harmonics are 3 times, 5 times, 8 times and 10 times, among which the maximum third harmonic is 0.17T.

3.3. Rated load simulation analysis
In rated load simulation analysis, the voltage source excitation is used, and the results can be used to analyze the performance of the motor.

As shown in Figure 7 and Figure 8, under rated load, the distribution of magnetic line in each part is reasonable, and the magnetic flux density is within a normal range.

The electromagnetic torque is shown in Figure 9, with the maximum value of 3.28N·m and the average value of 2.34 N·m in stable state. The torque ripple rate is small, which indicates a good output characteristics. The winding current in stable operation is an ideal sine wave with an effective value of 2.04A.

The core loss is composed of hysteresis loss and eddy current loss; while the stranded loss is mainly caused by the resistance when the current flows through the winding. In rated load state, the average
core loss and copper loss are 8.58W and 38.81W respectively. And the efficiency of the motor is up to 92.32%.

4. Conclusions
Based on the design requirements, this paper determines the initial sizes and important parameters of the motor, establishes calculation model and carries out optimum electromagnetic design to obtain final design scheme. And the operation performance of the motor under no-load and load conditions is simulated by finite-element method to verify the rationality of the motor design.

The results show that the distribution of electromagnetic field of the motor is uniform and reasonable under no-load and load, and the magnetic density is relatively high but not saturated, and the magnetic material is fully utilized. At the same time, the no-load back EMF and radial air gap flux density are designed reasonably; while the torque ripple rate is small and the output characteristic is good under the load condition. The design parameters and performance can meet the technical and operational requirements, which can provide the basis for further optimization and provide reference for the next prototype development.

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