

Design and Analysis of a Direct-Drive Permanent Magnet Synchronous Motor for Electric Screw in Robotic Arms: Postprint

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Abstract

Hydraulic drives exhibit low transmission efficiency, oil leakage, and high-temperature-induced fire hazards. This paper employs a permanent magnet synchronous motor with screw direct drive to replace the hydraulic drive link in robotic arms, converting the parameters of an excavator boom cylinder into those of a permanent magnet synchronous motor rated at $P_N = 22\text{kW}$, $n_N = 750\text{r/min}$. Two motor designs are developed: a 6-pole 36-slot configuration and an 8-pole 48-slot configuration, with no-load simulations performed in Maxwell. By adopting a rotor with non-uniform air gap to optimize the motor's air-gap magnetic flux density waveform and cogging torque, and conducting load simulations, a permanent magnet synchronous motor suitable for replacing hydraulic cylinders in robotic arms is obtained.

Full Text

Preamble

Design and Analysis of Permanent Magnet Synchronous Motor With Electric Screw for Arm

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Abstract

Hydraulic drive systems suffer from low transmission efficiency, oil leakage, and fire hazards at high temperatures. This paper proposes replacing the hydraulic drive unit of mechanical arms with a permanent magnet synchronous motor (PMSM) directly driving a screw mechanism. The parameters of an excavator boom cylinder are converted to PMSM parameters of $P_N = 22$ kW and $n_N = 750$ r/min. Two motor designs are developed: a 6-pole 36-slot configuration and an 8-pole 48-slot configuration, with no-load simulations performed in Maxwell. The air-gap magnetic flux density waveform and cogging torque are optimized using a rotor with non-uniform air gap, followed by load simulations. The result is a permanent magnet synchronous motor that can replace hydraulic cylinders in mechanical arms.

Keywords: Hydraulic drive, permanent magnet synchronous motor, screw drive, torque optimization

1 Introduction

Large mechanical equipment such as excavators, bulldozers, loaders, and graders rely heavily on large mechanical arms as primary components. Consequently, the performance of their drive systems directly impacts the stability and safety reliability of the entire working mechanism. Current large mechanical arms predominantly employ hydraulic control systems, which offer wide speed regulation ranges and compact, lightweight transmission devices [1-3]. However, hydraulic systems for construction equipment mechanical arms exhibit several significant drawbacks:

First, hydraulic systems operate through a hydraulic pump that converts mechanical energy into fluid pressure energy, which then drives the load. This two-stage energy conversion process results in low transmission efficiency. Second, hydraulic oil leakage at pipe joints is unavoidable, causing environmental pollution. Third, hydraulic oil properties, particularly viscosity, are highly temperature-dependent. As temperature increases, the viscous resistance and friction losses in pipelines increase, and heat accelerates aging of sealing rubber, leading to seal failure [4]. Moreover, high temperatures pose fire hazards. Fourth, due to the large size of construction equipment and numerous hydraulic transmission stages with extensive piping, the structure is complex. When faults occur, pinpointing the failure location is difficult, often relying on experience, making maintenance challenging [5-6] and demanding high technical expertise from maintenance personnel.

Current research on large mechanical arm drive systems remains confined to optimizing hydraulic system design, failing to break free from the inherent limitations of hydraulic drive. Only by changing the drive method can these fundamental problems be solved. Therefore, this paper proposes using a permanent magnet synchronous motor with a direct-drive screw system to replace hydraulic drives, as illustrated in [Figure 1: see original paper].

2 Parameter Conversion and Screw Selection

This analysis uses a single-boom cylinder excavator with a bucket capacity of 0.33 m^3 as an example. The boom cylinder parameters are listed in .

For a differential-advancing piston rod (where both sides of the piston are supplied with pressure oil simultaneously), the thrust is calculated as:

$$F = (A_1 - A_2)p \times 10^6 = d^2p \times 10^6$$

where A_1 is the effective area of the piston rod side (m^2), A_2 is the effective area of the non-rod side (m^2), p is the supply pressure (working oil pressure) in MPa, and d is the piston rod diameter in meters.

The calculated axial thrust is $F = 86.276 \text{ kN}$, yielding an output power of $P = Fv \approx 22 \text{ kW}$. Therefore, the rated power of the synchronous motor is set as $P_N = Fv \approx 22 \text{ kW}$.

A ball screw assembly with a lead of $P_h = 20 \text{ mm}$ is selected. The rotational speed is calculated as $n = 750 \text{ r/min}$. With the motor shaft directly coupled to the screw, the motor's rated speed is $n_N = 750 \text{ r/min}$.

The motor-screw transmission system utilizes the relative motion between screw and nut to convert the motor's rotary motion into linear motion, transforming torque into thrust [7]. Reference [8] proposed a flexible-joint manipulator driven by electric push rods instead of hydraulic cylinders, demonstrating through calculations and simulations that electric push rods provide greater driving force and gripping force with good dynamic performance. In the press machine domain, Japanese Enomoto Company and German Müller Weingarten Company successfully developed AC servo motor-driven CNC electric screw presses, avoiding complex hydraulic drive systems. In pneumatics, screw compressors have gradually replaced reciprocating air compressors [10] with superior economic benefits. These studies and applications provide valuable references for this research.

According to ball screw design principles, the equivalent load is calculated as:

$$C_{am} = f_w F_m \sqrt[3]{\frac{60n_m L_h f_a}{10^6 f_c}}$$

where f_a is the precision coefficient (), f_c is the reliability coefficient (), f_w is the load property coefficient (), and L_h is the expected working life ().

By selecting appropriate coefficients and substituting them into the equation, the equivalent load is calculated as $C'_a m = 364.314 \text{ kN}$. A model HFH63×20 screw is selected to meet the requirements.

3 Electromagnetic Design

Based on a rated power of $P_N = 22$ kW and rated speed of $n_N = 750$ r/min, the stator outer diameter is set at 310 mm. Two permanent magnet synchronous motors with different pole-slot configurations—6-pole 36-slot and 8-pole 48-slot—are designed while maintaining similar air gap length, no-load back EMF, and thermal load. The main parameters of both motors are listed in .

Models are established in Maxwell software, and no-load simulations are performed with zero excitation current. The no-load magnetic flux density cloud diagrams are shown in [Figure 2a: see original paper] and [Figure 2b: see original paper].

The maximum tooth flux density of the 8-pole 48-slot motor is 1.5998 T, which falls within the reasonable range for permanent magnet synchronous motors. The no-load radial air-gap magnetic flux density waveforms are shown in [Figure 3: see original paper] and [Figure 4: see original paper].

Harmonic analysis of the no-load radial air-gap magnetic flux density reveals the percentage of each harmonic relative to the fundamental, as shown in [Figure 5: see original paper]. The results indicate that the 3rd harmonic, which is the dominant component, accounts for 31.2% of the fundamental in the 6-pole 36-slot motor—significantly higher than the 29.09% in the 8-pole 48-slot motor. The 3rd harmonic is also the primary cause of no-load cogging torque, resulting in considerably higher cogging torque in the 6-pole 36-slot motor compared to the 8-pole 48-slot motor, consistent with simulation results. The cogging torque waveforms are shown in [Figure 6: see original paper] and [Figure 7: see original paper], with cogging torque accounting for 5.23% and 3.49% of rated torque for the 6-pole 36-slot and 8-pole 48-slot motors, respectively.

4 Optimization

To reduce torque ripple caused by cogging torque, this paper employs a 1.5-times non-uniform air gap design in the rotor laminations to optimize the radial air-gap magnetic flux density waveform and cogging torque. The harmonic decomposition of the resulting no-load radial air-gap magnetic flux density is shown in [Figure 8: see original paper].

After optimization with non-uniform air gap, the 3rd harmonic content in the 6-pole 36-slot motor remains higher than in the 8-pole 48-slot motor. However, compared with [Figure 5: see original paper], the 3rd harmonic content is significantly reduced for both configurations, with decreases of 3.71% and 4.35%, respectively. Correspondingly, the cogging torque is reduced to 3.7% of rated torque for the 6-pole 36-slot motor and 1.83% for the 8-pole 48-slot motor, fully meeting excavator boom cylinder stability requirements.

To verify that the permanent magnet synchronous motor can replace the hydraulic drive system in terms of output capability, load simulations are performed on both optimized motors. Under rated current excitation, the rated

torque values are obtained as shown in . Analysis demonstrates that by controlling the current angle within a specific range, the torque provided by the permanent magnet synchronous motor can satisfy the output requirements of excavator boom cylinders.

5 Conclusion

This paper converts hydraulic parameters from a 0.33 m³ single-boom cylinder hydraulic excavator and designs two permanent magnet synchronous motors with different pole-slot configurations. Through analysis and optimization, the following conclusions are drawn:

1. Hydraulic parameters of excavator boom cylinders can be reasonably converted to power and speed specifications for permanent magnet synchronous motors in electric screw direct-drive systems through appropriate calculations of axial thrust and motion velocity.
2. Simulations reveal that different pole-slot configurations result in varying 3rd harmonic content in the radial air-gap magnetic flux density, with the 6-pole 36-slot design exhibiting higher harmonic content than the 8-pole 48-slot design.
3. The 3rd harmonic content significantly affects cogging torque magnitude, with higher 3rd harmonic content leading to greater cogging torque.
4. Non-uniform air gap achieved through rotor lamination design can effectively reduce 3rd harmonic content in the radial air-gap magnetic flux density while simultaneously decreasing cogging torque.
5. The permanent magnet synchronous motor with direct-drive screw system can replace hydraulic drive systems in mechanical arms.

Adopting permanent magnet synchronous motor screw direct-drive systems instead of hydraulic drive units not only avoids problems of low transmission efficiency, oil leakage, environmental pollution, and fire hazards at high temperatures, but also provides a theoretical foundation for precise digital control of large mechanical equipment arms, representing significant practical importance.

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