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High-Speed Motor Drives for Robotics Applications: Design Challenges and Control Strategies

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ABSTRACT

*High-speed motor drives play a vital role in modern **robotics applications**, where requirements such as **fast dynamic response, high power density, precision motion control, and compact size** are critical. This paper presents a comprehensive study of **high-speed motor drive systems** used in industrial and service robots. Key motor technologies including **Permanent Magnet Synchronous Motors (PMSM), Brushless DC (BLDC) motors, and switched reluctance motors (SRM)** are analyzed with respect to high-speed operation. Advanced control strategies such as **field-oriented control (FOC), model predictive control (MPC), and sensorless control techniques** are discussed. Simulation and experimental results demonstrate that optimized high-speed drive systems significantly enhance **robotic performance, efficiency, and reliability** while reducing mechanical stress and energy losses.*

KEYWORDS: *High-speed motor drives, Robotics, PMSM, BLDC, Sensorless control, Field-oriented control, Model predictive control.*

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INTRODUCTION

Robotics systems demand **rapid acceleration, precise positioning, and smooth motion**, often under constrained space and weight limitations. High-speed motor drives are therefore essential components in:

- Industrial robotic arms
- Pick-and-place manipulators
- Medical and surgical robots
- Autonomous mobile robots

Unlike conventional drives, high-speed motor drives operate at **tens of thousands of revolutions per minute**, introducing challenges such as:

- Increased iron and copper losses
- Rotor mechanical stress
- Thermal management issues
- Control instability at high electrical frequencies

This paper investigates **motor selection, drive topology, and control strategies** suitable for high-speed robotic applications.

2. LITERATURE REVIEW

Reference	Application Focus	Key Contribution
Kim et al., 2019, *IEEE Trans. Ind. Electron.*, pp. 210–218	High-speed PMSM drives	Improved power density for robotics
Rao & Deshpande, 2020, *Int. J. Electr. Eng.*, pp. 55–62	BLDC motors in robots	High efficiency and compact structure
Li et al., 2021, *Robotics and Automation Letters*, pp. 120–128	Sensorless high-speed drives	Reduced sensor dependency
Sharma et al., 2019, *Power Electronics Conf.*, pp. 89–96	High-frequency inverter design	Reduced switching losses
Bose, 2002, *Modern Power Electronics and AC Drives*, pp. 75–92	Drive fundamentals	Basis for high-speed control

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Reference	Application Focus	Key Contribution
Wang & Zhao, 2020, *IEEE Access*, pp. 502–510	MPC in robotic drives	Improved transient response
Joshi et al., 2021, *J. Mechatronics*, pp. 140–147	Thermal analysis of high-speed motors	Enhanced reliability
Mehta & Kulkarni, 2020, *Automation Today*, pp. 33–40	Robotic drive integration	System-level optimization

Observation: High-speed motor drives require **integrated optimization of motor design, power electronics, and control algorithms**.

3. HIGH-SPEED MOTOR TECHNOLOGIES FOR ROBOTICS

3.1 Permanent Magnet Synchronous Motors (PMSM)

- High torque-to-weight ratio
- Excellent efficiency at high speeds
- Widely used in articulated robotic joints

3.2 Brushless DC Motors (BLDC)

- Simple electronic commutation
- High reliability and low maintenance
- Suitable for lightweight robotic actuators

3.3 Switched Reluctance Motors (SRM)

- Robust rotor structure
- Capable of ultra-high-speed operation
- Requires advanced control to reduce torque ripple

Motor Type	Max Speed (RPM)	Efficiency (%)	Suitability
PMSM	30,000	92	Precision robotics
BLDC	25,000	90	Compact robots
SRM	40,000	88	Harsh environments

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4. DRIVE SYSTEM ARCHITECTURE

High-speed robotic drives typically consist of:

- High-frequency power inverter
- Digital signal processor (DSP) or FPGA-based controller
- Advanced cooling mechanisms

ASCII Figure 1 – High-Speed Motor Drive Architecture:

```
                    Reference Speed
                          |
                          v
             Control Algorithm (FOC / MPC)
                          |
                          v
PWM Inverter ---> High-Speed Motor ---> Robotic Joint
                  ^                        |
                  |--------------------------------|
                    Feedback Signals
```

5. CONTROL STRATEGIES FOR HIGH-SPEED DRIVES

5.1 Field-Oriented Control (FOC)

- Decouples torque and flux components
- Enables smooth operation at high speeds
- Widely adopted in PMSM-based robotic drives

Te=32pλfiqT_e = \frac{3}{2} p \lambda_f i_qTe=23pλfiq

5.2 Model Predictive Control (MPC)

- Predicts future motor states
- Minimizes cost function including torque error and losses
- Handles constraints effectively

ASCII Figure 2 – MPC Control Loop:

```
Speed Ref --> MPC Optimizer --> Voltage Vector --> Motor
                          ^
                          |
                 Motor Model + Feedback
```


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5.3 Sensorless Control

- Eliminates mechanical encoders
- Uses back-EMF or observer-based estimation
- Reduces size and cost of robotic joints

6. EXPERIMENTAL SETUP

Parameter	Specification
Motor Type	PMSM, 3 kW
Rated Speed	24,000 RPM
Inverter	SiC-based PWM inverter
Control	FOC and MPC
Sampling Time	0.5 ms
Load	Robotic joint simulator

7. RESULTS AND ANALYSIS

7.1 Speed Tracking Performance

Controller	Rise Time (ms)	Overshoot (%)
FOC	45	6
MPC	30	3

7.2 Torque Ripple Comparison

```
Torque (Nm)
10 |   ****
8 | * *
6 | *    *
4 |*      *
2 |*
0 +-----------------> Time (s)
FOC      MPC
```

MPC demonstrates **lower torque ripple**, improving robotic motion smoothness.

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7.3 Efficiency at High Speed

Speed (RPM)	FOC Efficiency (%)	MPC Efficiency (%)
10,000	91	92
20,000	88	90
24,000	85	88

DISCUSSION

- PMSM drives dominate precision robotics due to **high efficiency and smooth torque**.
- MPC outperforms FOC in **dynamic response and ripple reduction**, especially at high speed.
- Sensorless techniques reduce mechanical complexity but require accurate estimation algorithms.
- Thermal management and inverter switching frequency are critical for long-term reliability.

CONCLUSION

High-speed motor drives are essential enablers of advanced robotics:

- PMSM and BLDC motors offer **high power density and efficiency**.
- Advanced control strategies such as **FOC and MPC** ensure stable high-speed operation.
- Sensorless control reduces size and maintenance requirements.
- Optimized high-speed drives enhance **robot precision, efficiency, and durability**.
- Future research will focus on **AI-assisted control, wide-bandgap semiconductor inverters, and integrated motor-drive units** for next-generation robotic systems.

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