ISSN: 2472-3703 DOI: 10.6911/WSRJ.202603_12(3).0004

# Permanent Magnet Synchronous Motor Drive Control for High-Temperature Downhole Formation Sampling: Design and Experimental Validation

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## Abstract

**Downhole formation sampling requires stable motor control under high temperature and strong vibration. This paper presents an integrated permanent magnet synchronous motor (PMSM) control-drive system for a compact downhole sampling tool. The system combines miniaturized hardware, resolver-based feedback, field-oriented control, and an improved fuzzy two-degree-of-freedom PI speed controller to enhance low-speed stability and turn-count accuracy. Experiments were carried out under no-load, load, high-temperature, and vibration conditions. Results show that the system operates reliably at 150 °C and 20 g vibration, with steady-state speed error below 1% full scale and full-scale relative turn-count error below 0.5%. The proposed design provides a practical high-temperature motor-drive solution for downhole formation sampling tools.**

## Keywords

**Downhole formation sampling; PMSM; Integrated drive and control.**

## 1. INTRODUCTION

Downhole formation sampling has become an important technique in modern oil and gas exploration because it enables in-situ acquisition of formation fluids and supports more accurate reservoir evaluation. In practical drilling environments, however, sampling tools are required to operate under extremely harsh conditions, including elevated ambient temperatures, intense vibration, and limited installation space. According to available reports, downhole coring and logging tools may be required to function reliably at temperatures exceeding 200 °C [1]. Owing to their high power density, high efficiency, and compact structure, permanent magnet synchronous motors (PMSMs) have been widely considered for such downhole actuation systems [2]. Nevertheless, the low-speed and heavy-load operating characteristics of formation sampling place stringent requirements on motor control performance, and conventional PI-based strategies often face difficulties in simultaneously achieving fast dynamic response and high steady-state accuracy. To overcome these limitations, intelligent control methods, particularly fuzzy-control-based approaches, have been introduced into PMSM drive systems [3]. Existing studies, however, have mainly concentrated on controller design within the field-oriented control (FOC) framework, while relatively limited attention has been paid to the integrated implementation and experimental validation of PMSM drive systems for downhole sampling tools under high-temperature conditions. In view of this issue, this paper develops an integrated PMSM drive and control system for downhole formation sampling and adopts a fuzzy two-degree-of-freedom PI control strategy. The effectiveness of the proposed system is experimentally verified under low-speed operation and elevated-temperature conditions.

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# 2. SYSTEM DESIGN

## 2.1. Technical Requirements and Overall Architecture

The proposed drive system was developed for a downhole formation sampling actuator operating under harsh environmental conditions. The main design targets include a rated torque of 15 N·m, a rated speed of 580 rpm, and reliable operation at 150 °C. To satisfy these requirements, an integrated control-drive architecture was designed, as shown in Fig. 1.

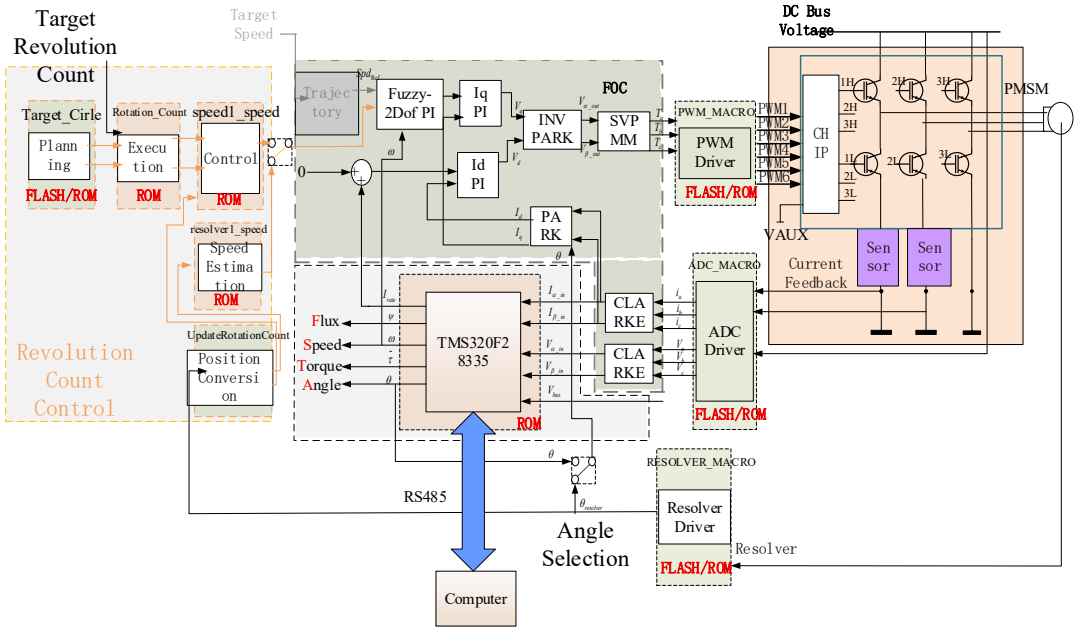



**Figure 1.** Schematic of the integrated PMSM drive and control system with position feedback

The system employs a TMS320F28335 DSP as the main controller and a three-phase inverter to drive the PMSM. Resolver feedback is introduced for rotor position and speed acquisition, while current and temperature signals are sampled for closed-loop control and condition monitoring. This architecture provides a compact and practical solution for downhole sampling tools with strict space and environmental constraints.

## 2.2. Control Strategy

The motor control system is implemented based on the field-oriented control (FOC) framework. The outer speed loop generates the q-axis current reference, and the inner current loops regulate the q-axis and d-axis currents, with the d-axis current reference set to zero. Space vector pulse width modulation (SVPWM) is adopted to generate inverter switching signals. To improve low-speed tracking performance, a fuzzy two-degree-of-freedom PI controller is introduced into the speed loop. Compared with conventional PI control, this strategy provides a better balance between dynamic response and steady-state accuracy. The overall control flow is shown in Fig. 2.

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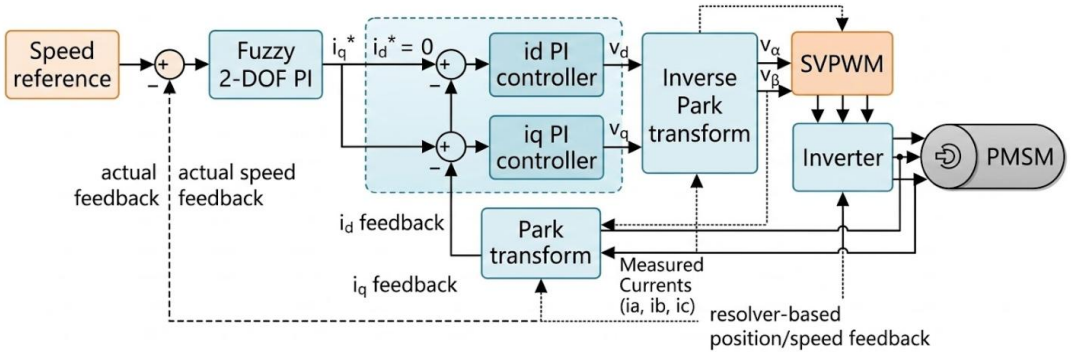



**Figure 2.** Control structure of the proposed PMSM drive system with fuzzy two-degree-of-freedom PI speed regulation

## 3. HARDWARE IMPLEMENTATION

### 3.1. Hardware Architecture

The proposed PMSM drive system was implemented using an integrated control-drive hardware architecture, as shown in Fig. 3.

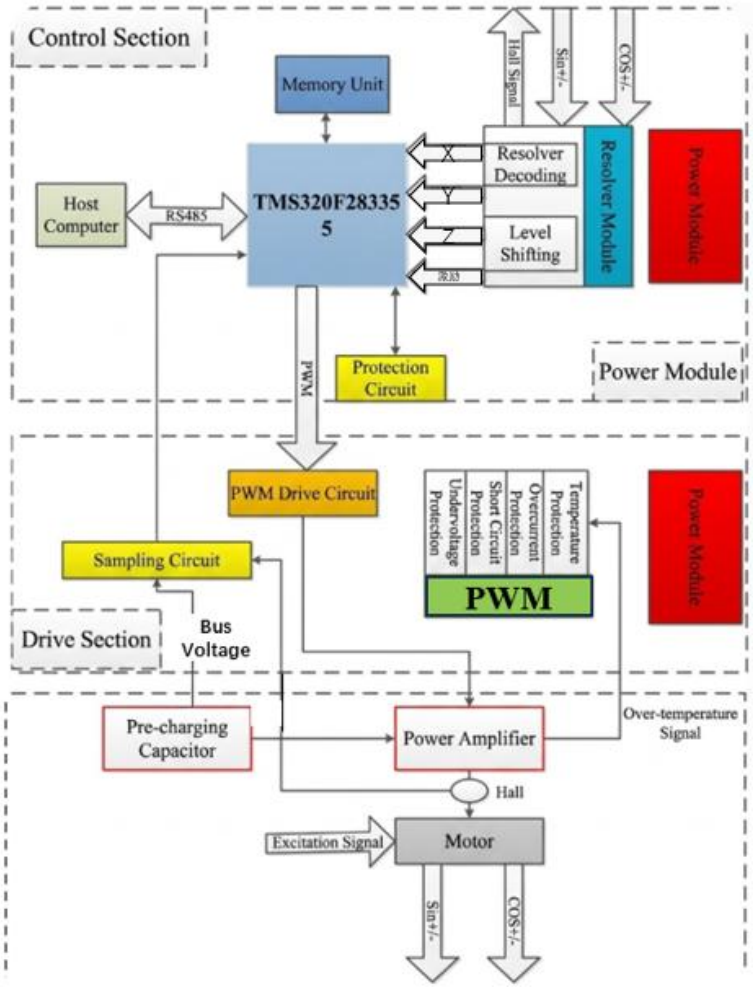



**Figure 3.** Overall hardware architecture of the proposed integrated PMSM drive system

The hardware mainly consists of a DSP-based control module, a power conversion module, sensor interface circuits, and communication circuits. The control module is responsible for signal acquisition, control computation, and PWM generation, while the power conversion module drives the three-phase PMSM. Resolver feedback is employed for rotor position and

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speed measurement, and current and temperature sensing circuits are included to support closed-loop control and system monitoring. To satisfy the requirements of downhole operation, high-temperature electronic components were selected and a multilayer printed circuit board was designed to improve structural compactness, thermal adaptability, and anti-interference capability.

### 3.2. Software Implementation

The software was implemented on the TMS320F28335 DSP with a layered structure consisting of system initialization, real-time control interrupts, background monitoring, and host-computer communication. At startup, the program completes peripheral configuration, resolver interface initialization, ADC and PWM configuration, parameter loading, and fault-state initialization. After initialization, the real-time control tasks are executed in a periodic interrupt routine. as shown in Fig. 4.

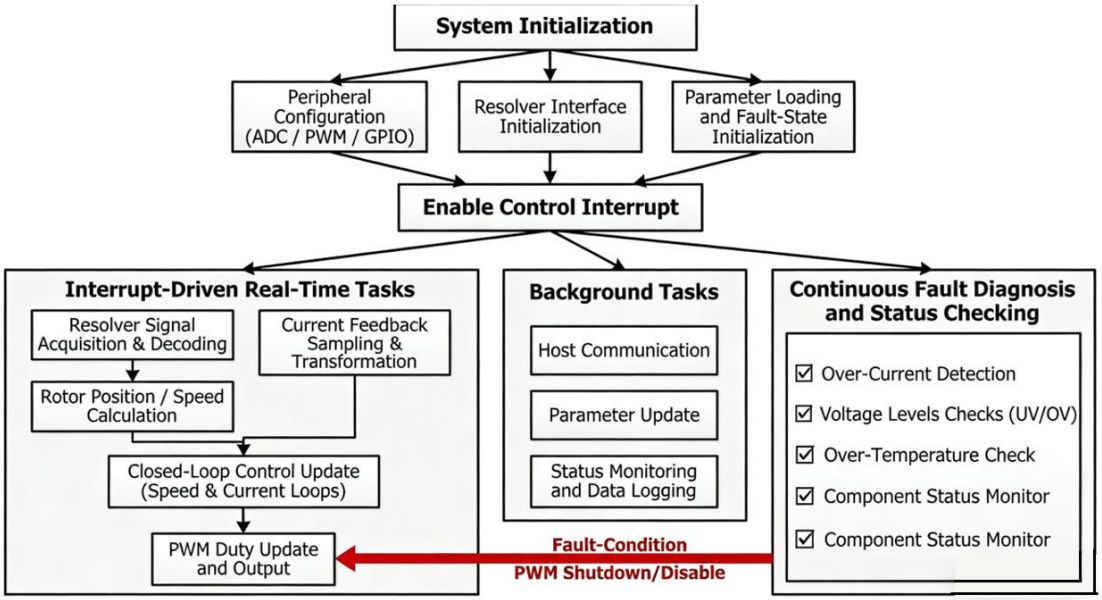



**Figure 4.** Software architecture and task organization of the proposed DSP-based PMSM drive system

Within the interrupt cycle, resolver signals are acquired and processed first to obtain rotor position and speed information. The current feedback signals are then sampled and transformed for closed-loop regulation. The speed loop and current loops are executed according to their respective update rates, and the computed voltage commands are further converted into PWM duty cycles for inverter driving. In parallel, fault diagnosis and status checking are continuously performed to ensure safe operation of the drive system.

In addition to the real-time control tasks, background software functions were developed for parameter update, operating-state monitoring, data transmission, and host-computer interaction. This implementation enables coordinated execution of motion control, signal acquisition, protection logic, and communication functions on a single DSP platform, providing software support for subsequent experimental verification of the proposed drive system.

## 4. EXPERIMENTAL RESULT

To verify the high-temperature adaptability of the proposed PMSM drive and control system, the integrated control-drive board was tested in a 175 °C thermal chamber, as shown in Fig. 5.

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**Figure 5.** High-temperature experimental setup of the proposed PMSM drive system at 175 °C

Under this condition, the motor was commanded to perform low-speed tracking operation, and the corresponding speed response is shown in Fig. 6.

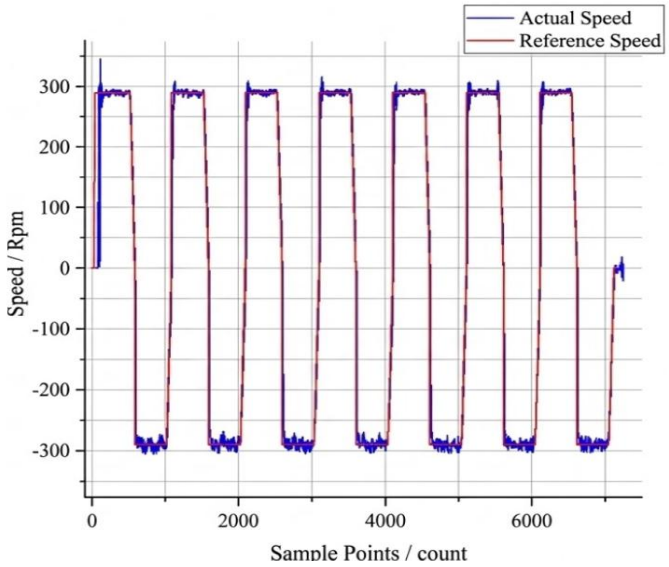



**Figure 6.** Speed-tracking response of the proposed system under high-temperature conditions

The experimental results indicate that the proposed system maintained stable operation throughout the test, and no abnormal oscillation, loss of synchronism, or control failure was observed. The measured speed followed the reference well, demonstrating that the proposed control strategy remained effective under elevated-temperature conditions.

To further evaluate the reliability of motion feedback at high temperature, the turn-counting result obtained under the same test condition is presented in Fig. 7.

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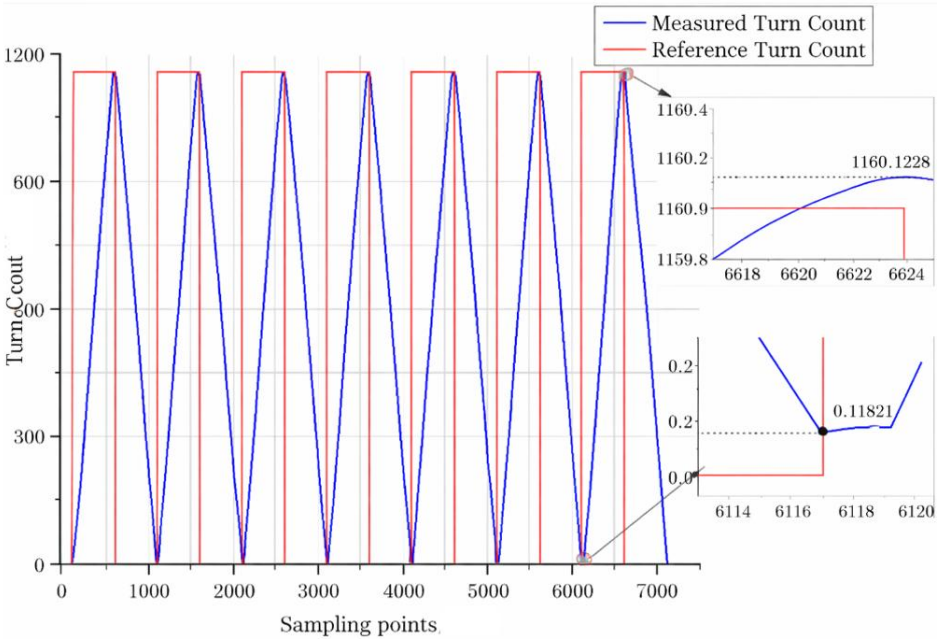



**Figure 7.** Turn-counting result of the proposed system under high-temperature conditions

The measured cumulative turns agree well with the reference value, and the counting error remains within the design requirement. These results confirm that the proposed system can simultaneously achieve stable speed regulation and accurate turn-count measurement at 175 °C, thereby validating the feasibility of the integrated high-temperature design for downhole formation sampling applications.

## ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to all those who provided support and assistance during this study. Special thanks are extended to the supervisors and colleagues for their valuable guidance, technical discussions, and experimental support. The authors also appreciate the help provided in the design, implementation, and testing of the proposed system.

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