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Motor and Bearing Temperature Monitoring of Milling Machine Based on Plc-Scada

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ABSTRACT

This study addresses the growing need for reliable thermal monitoring systems in industrial milling machines, particularly for spindle motors and bearings that are highly vulnerable to overheating during continuous machining operations. Excessive temperature can reduce component lifespan, increase maintenance costs, and cause unexpected production downtime. Therefore, this research aims to design and evaluate a PLC-SCADA-based temperature monitoring system capable of providing real-time monitoring, automatic alarm response, and historical data logging for milling machine operation. The research employed an experimental engineering approach using a Siemens S7-1200 PLC integrated with PT100 RTD temperature sensors, Modbus TCP/IP communication, and SIMATIC WinCC Flexible SCADA software. Four PT100 sensors were installed on the spindle motor and bearing housings to acquire thermal data continuously during idle, medium-load, and full-load machining conditions. The results demonstrated that the system successfully monitored temperature in real time with a SCADA update latency below 200 ms and communication latency averaging 3.6 ms. The maximum spindle motor temperature reached 98.4°C during full-load operation, while the implemented warning and automatic cooling system successfully prevented critical overheating conditions. Temperature measurement accuracy achieved a mean absolute error of 0.41°C compared with the reference instrument. In conclusion, the proposed PLC-SCADA monitoring system effectively improves machine reliability, operational safety, and predictive maintenance capability in industrial milling machine applications.

INTRODUCTION

The milling machine is one of the most vital mechanical assets in modern manufacturing processes, widely employed for metalworking operations such as surface milling, slot cutting, and complex contour forming. The primary components of a milling machine that are most susceptible to thermal failure are the spindle drive motor and the bearings supporting the main shaft (Bouraiou et al., 2021; Randall, 2021). Overheating of the motor and bearings not only shortens the service life of those components but may also lead to unexpected machine failure, production losses, and safety hazards for operators (Hodowanec et al., 2024; Kumar & Satapathy, 2023; Madonna et al., 2019).

According to IEC 60034-1, three-phase induction motors used in machine tools generally have a maximum operating temperature based on their insulation class: Class B (130°C) and Class F (155°C). In industrial practice, however, the safe operational limit for milling machine motors is often set more conservatively at 80–100°C to sustain long-term reliability. Bearings, as rotating components in direct contact with dynamic loads, are particularly sensitive to temperature variations; an increase of 10°C above the nominal bearing temperature is known to reduce lubricant service life by up to 50% (Rashid, 2017).

Conventional monitoring approaches that rely solely on manual inspection or handheld thermometers have significant limitations: they provide no continuous data, cannot issue automatic early warnings, and do not store historical data for failure trend analysis (Siemens AG, 2022). A more effective approach is the integration of a PLC-based data acquisition system with a SCADA (Supervisory Control and Data Acquisition) interface, enabling real-time thermal monitoring, historical data logging, multi-level alarm management, and automatic response to abnormal conditions (Mansour et al., 2020).

Several prior studies have explored PLC- and SCADA-based monitoring systems for industrial equipment (Engin et al., 2021; Rashad et al., 2022; Tomar & Kumar, 2020). Kurniawan et al. (2023) implemented a vibration and temperature monitoring system for induction motors using a Raspberry Pi and Mitsubishi PLC, demonstrating that real-time monitoring can detect bearing degradation 72 hours before total failure. Pramono et al. (2022) developed a LabVIEW-based SCADA system for CNC milling machine condition monitoring, achieving temperature measurement accuracy of ±0.5°C. Widodo and Saputra (2022) investigated the integration of PT100 sensors with a Siemens S7-300 PLC for servo motor thermal monitoring, proving that PLC-based approaches offer higher reliability than standalone microcontroller systems. Abdullah et al. (2020) demonstrated the use of Modbus TCP/IP in industrial SCADA systems with communication latency below 5 ms. Building on these prior works, this paper presents a fully integrated PLC-SCADA system specifically designed for motor and bearing temperature monitoring of a milling machine.

The global manufacturing sector increasingly recognizes that machine downtime is not merely a technical problem but also a strategic economic risk. Predictive maintenance research reports that the median unplanned downtime cost across eleven industries is approximately USD 125,000 per hour, meaning that even short failures can generate substantial production losses. Recent industry reports also show that manufacturers continue to experience frequent downtime events, confirming that reliability, condition monitoring, and early-warning systems remain urgent priorities for industrial facilities. Therefore, real-time monitoring of temperature in critical machine components is essential because overheating can reduce component life, interrupt production schedules, and create safety risks for operators.

The specific problem addressed in this research lies in the thermal vulnerability of milling machine motors and bearings. The manuscript explains that the spindle drive motor and shaft-supporting bearings are the most susceptible components to thermal failure, where overheating may shorten service life, damage insulation, reduce lubrication performance, and trigger unexpected machine stoppage. The paper also notes that industrial practice commonly sets conservative motor temperature limits at 80–100°C, while bearing temperature increases can accelerate lubricant degradation and mechanical wear. These conditions indicate that manual inspection or occasional handheld temperature measurement is no longer sufficient for modern machining systems that require continuous operation, rapid detection, automatic warning, and historical trend analysis.

Several relevant previous studies have shown the importance of integrating industrial automation with condition monitoring. Kurniawan et al. developed a vibration and temperature monitoring system for induction motors using Raspberry Pi and Mitsubishi PLC, demonstrating that real-time monitoring could detect bearing degradation before total failure. Pramono et al. designed a LabVIEW-based SCADA system for CNC milling machine condition monitoring with temperature measurement accuracy of ±0.5°C. Widodo and Saputra integrated PT100 sensors with Siemens S7-300 PLC for servo motor thermal monitoring, while Abdullah et al. reported that Modbus TCP/IP communication can support low-latency industrial SCADA applications. These studies are also cited in the uploaded manuscript as the main foundation for developing a PLC-SCADA-based milling machine temperature monitoring system.

Recent research further confirms the continued relevance of this topic. A 2026 study on IoT-based three-phase induction motor control reported real-time monitoring of voltage, current, temperature, vibration, and speed, with communication latency maintained below 100 ms and maintenance-cost reduction potential of 15%. Another 2025 study on CNC machine spindle bearing monitoring used PLC and SCADA for vibration-based damage prediction, showing that automated monitoring has become increasingly important in machine-tool reliability research. In addition, research on PLC-SCADA-based induction motor protection emphasizes that thermal overload is one of the major causes of motor failure, strengthening the argument that temperature monitoring should be treated as a core maintenance function rather than a supplementary feature.

Despite these advances, a research gap remains in the development of an integrated, machine-specific, and experimentally validated PLC-SCADA system for simultaneous motor and bearing temperature monitoring in milling machines (Dharmawati, 2024). Many previous studies focus on general induction motors, vibration signals, IoT platforms, or laboratory-scale monitoring, while fewer studies provide a complete architecture that combines PT100 RTD sensing, Siemens PLC acquisition, Modbus TCP/IP communication, SCADA HMI visualization, alarm logging, automatic cooling response, and operational testing under actual milling load conditions (Dharmawati, 2024; Saravanan et al., 2024; Sharma et al., 2020). The uploaded manuscript attempts to fill this gap by designing a three-layer system consisting of field sensors and actuators, PLC-based control and acquisition, and SCADA-based supervision.

The urgency of this research is reinforced by the operational characteristics of milling machines, where spindle load, cutting material, machining duration, and bearing condition can rapidly influence thermal behavior. In the uploaded study, full-load testing showed that the spindle motor reached an average temperature of 87.6°C and a peak of 98.4°C, close to the critical threshold of 100°C. This finding proves that without continuous monitoring and automatic response, a milling machine operating under heavy load may approach unsafe thermal conditions. Therefore, the development of reliable PLC-SCADA monitoring is urgent to prevent failure escalation, protect expensive mechanical components, and improve maintenance decision-making.

The novelty of this research lies in its practical integration of industrial-grade components into a complete real-time temperature monitoring and alarm-response system for milling machines. The system uses four PT100 RTD sensors positioned on the spindle motor and bearing housings, Siemens S7-1200 PLC with SM 1231 RTD module, Modbus TCP/IP communication, and WinCC Flexible SCADA interface. It also implements two-level alarm logic, automatic cooling fan activation, event logging, and trend visualization. The study reports a mean absolute error of 0.41°C, SCADA update latency below 200 ms, and 100% cooling fan activation success during warning events, showing that the proposed system is not only conceptual but also experimentally verified.

The purpose of this research is to design, implement, and evaluate a PLC-SCADA-based temperature monitoring system that can continuously observe the thermal condition of milling machine motors and bearings. More specifically, the research aims to measure temperature accurately using PT100 RTD sensors, transmit data reliably through PLC and Modbus TCP/IP communication, display real-time information through SCADA HMI, record historical alarm events, and activate automatic cooling when warning thresholds are reached. By achieving these objectives, the study contributes to the transformation of maintenance practices from reactive manual inspection toward data-driven condition monitoring and predictive maintenance.

The expected contribution of this research is both theoretical and practical. Theoretically, it enriches the literature on industrial automation, machine condition monitoring, and SCADA-based predictive maintenance by providing empirical evidence on temperature behavior, measurement accuracy, communication latency, and alarm response in a milling machine environment. Practically, the system can help manufacturing workshops reduce overheating risk, improve operator awareness, extend motor and bearing service life, and support future integration with IoT dashboards, vibration sensors, and machine learning-based remaining useful life prediction. Therefore, this research benefits machine operators, maintenance engineers, production managers, and future researchers seeking to build more reliable, intelligent, and scalable monitoring systems for industrial machining equipment.

METHOD

System Architecture and Design

1. Overall System Architecture

The proposed PLC-SCADA temperature monitoring system is structured in three functional layers. The field layer comprises the vertical CNC milling machine, four PT100 RTD sensors (two on the spindle motor and two on the front and rear bearing housings), and cooling fan relay actuators. The control and acquisition layer consists of a Siemens S7-1200 PLC with an SM 1231 RTD expansion module that cyclically acquires temperature data at 100 ms intervals. The supervisory layer hosts an industrial PC running SIMATIC WinCC Flexible as the SCADA platform, connected to the PLC via a managed Ethernet network.

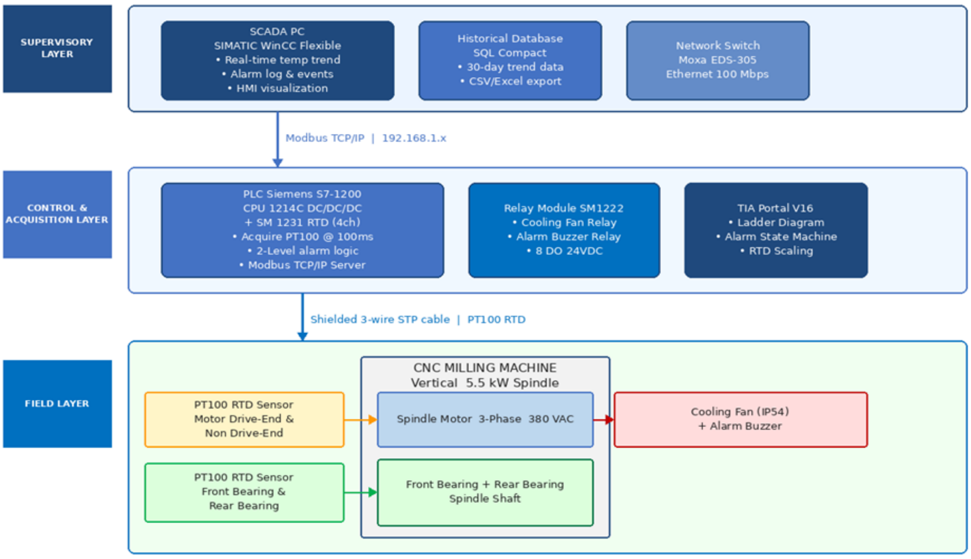


Figure 1. Three-layer system architecture of the PLC-SCADA temperature monitoring system for the milling machine.

2. Hardware Architecture

The hardware configuration is centered on the Siemens S7-1200 CPU 1214C DC/DC/DC PLC, expanded with an SM 1231 RTD module (6ES7231-5PD32-0XB0) providing four RTD channels. This model was selected for its ability to directly interface with PT100 sensors at 16-bit resolution and its integrated PROFINET port enabling Modbus TCP/IP server operation without an additional communication module. PT100 sensors (3-wire type) are mounted using dedicated machine-tool sensor clamps at strategic locations: two sensors on the spindle motor housing (drive-end and non-drive-end sides) and two sensors on the spindle shaft bearing housings (front and rear bearings), inserted 10 mm deep via stainless steel fittings to ensure accurate bearing inner ring temperature representation.

The cooling relay uses a Siemens SM 1222 8DO module controlled directly by PLC digital outputs. The control panel is housed in a NEMA 12 (IP54) enclosure mounted adjacent to the milling machine. All PT100 sensor cables are routed through separate metal conduits at a minimum distance of 300 mm from the spindle inverter power cables to minimize electromagnetic interference.

Table 1. Hardware and software components of the PLC-SCADA temperature monitoring system.

Parameter	Specification / Value
PLC Model	Siemens S7-1200 CPU 1214C DC/DC/DC
Digital Inputs	14 × 24 VDC (8 used for sensor signals and status)
Analog Inputs (RTD)	4-Channel PT100 via Expansion Module SM 1231 RTD
Communication	PROFINET / Modbus TCP/IP (Port 502)
Motor Temp. Sensor	PT100 RTD, Range 0–150°C, Accuracy ±0.3°C
Bearing Temp. Sensor	PT100 RTD, Range 0–200°C, Accuracy ±0.3°C
RTD Module	Siemens SM 1231 RTD (6ES7231-5PD32-0XB0)
SCADA Software	SIMATIC WinCC Flexible 2008 SP4

SCADA Hardware	Industrial PC, Intel Core i5, 8 GB RAM, Windows 10 IoT
Network Switch	Moxa EDS-305 5-port Managed Ethernet Switch
Milling Machine	CNC Vertical Milling Machine, Spindle 5.5 kW, 3-phase 380 VAC
Motor Alarm Threshold	Warning: 80°C | Critical: 100°C (Hysteresis: 5°C)
Bearing Alarm Threshold	Warning: 90°C | Critical: 110°C (Hysteresis: 5°C)

3. Software Design and PLC Programming

The PLC program was developed using TIA Portal V16 in Ladder Diagram (LD) and Function Block Diagram (FBD), organized into three Organization Blocks: OB1 (cyclic main program), OB30 (100 ms cyclic interrupt for RTD acquisition and scaling), and OB82 (diagnostic interrupt). The scaling function block converts raw integer values from the SM 1231 RTD module into temperature values in units of 0.1°C using linear interpolation. The scaled temperature values are then written to Modbus Holding Registers MW100–MW108, which the SCADA client polls every 200 ms.

The alarm logic is implemented as a two-level state machine: Warning (motor temperature ≥ 80°C, bearing temperature ≥ 90°C) and Critical (motor temperature ≥ 100°C, bearing temperature ≥ 110°C). Upon a Warning condition, the cooling fan relay is activated automatically via PLC digital output. Upon a Critical condition, the alarm buzzer relay is additionally activated and the critical alarm bit is written to a Holding Register to trigger a high-priority notification on the SCADA HMI. A 5°C hysteresis is applied to the alarm logic to prevent unnecessary relay chattering.

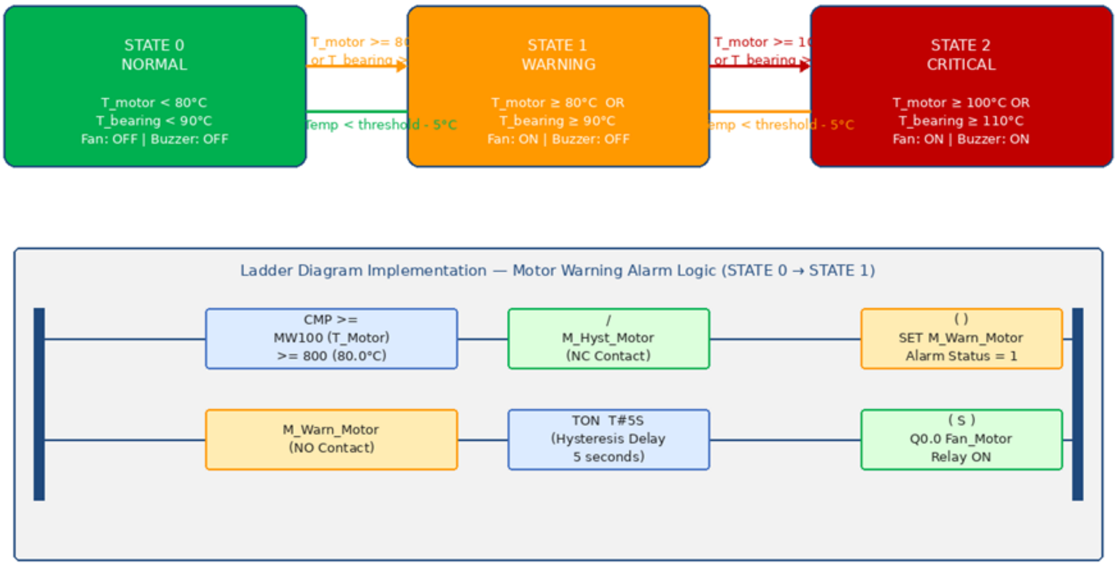


Figure 2. Two-level temperature alarm state machine implemented in Ladder Diagram on the Siemens S7-1200 PLC.

4. SCADA HMI Design

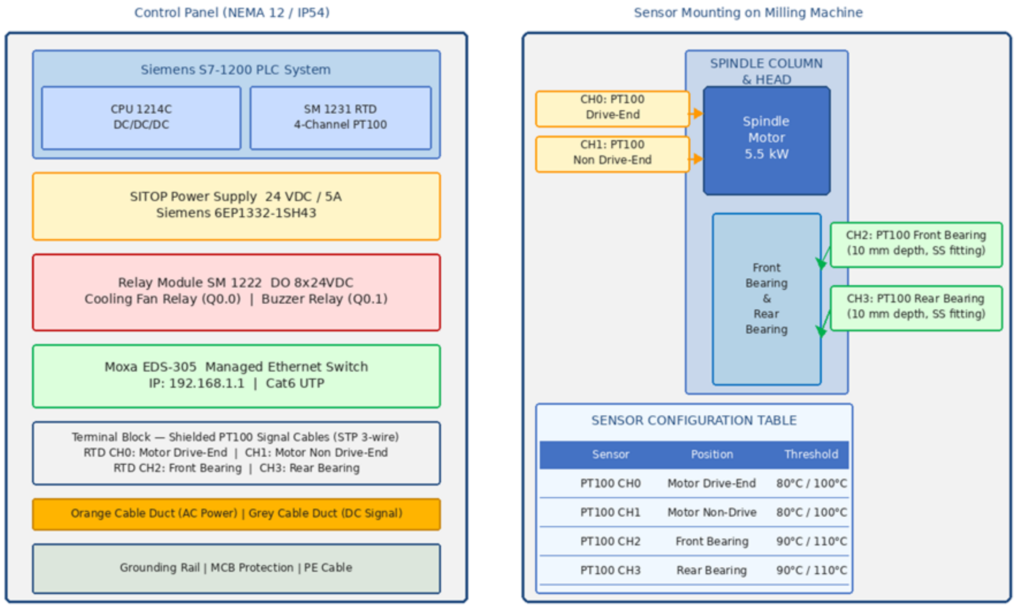
The SCADA HMI was designed in SIMATIC WinCC Flexible 2008 and consists of four primary screens: (1) the Main Overview screen displaying a graphical representation of the milling machine with dynamic real-time temperature indicators at each sensor point; (2) the Trend screen showing temporal trend charts for motor and bearing temperatures over the past 8 hours; (3) the Alarm Log screen listing all alarm events with timestamps and temperature values at the time of occurrence; and (4) the Settings screen for configuring alarm thresholds and polling parameters. Temperature indicators use a three-level color coding scheme in accordance with ISA-18.2: green (normal), amber/orange (warning), and red (critical).

Implementation

1. Hardware Implementation

The control panel was constructed in a NEMA 12 enclosure measuring 500 × 600 × 200 mm with a 3 mm galvanized steel backplate. The Siemens S7-1200 PLC and SM 1231 RTD module are mounted on a DIN rail in the upper section of the panel, alongside a SITOP 24 VDC power supply. All PT100 sensor signal cables use shielded twisted-pair (STP) 3-wire conductors of 0.75 mm² cross-section, routed in separate metal conduits at a minimum of 300 mm from the spindle inverter power cables to minimize electromagnetic interference.

PT100 sensors on the motor are mounted using thermal compound-coated sensor clamps to ensure good thermal contact between the sensor tip and the motor housing surface. On the bearings, PT100 sensors are inserted through prepared holes in the bearing housing using stainless steel fittings at a depth of 10 mm from the outer housing surface, ensuring a thermal response representative of the actual bearing inner ring temperature.



Sensor	Position	Threshold
PT100 CH0	Motor Drive-End	80°C / 100°C
PT100 CH1	Motor Non-Drive	80°C / 100°C
PT100 CH2	Front Bearing	90°C / 110°C
PT100 CH3	Rear Bearing	90°C / 110°C

Figure 3. Control panel layout of the PLC-SCADA system and PT100 sensor mounting positions on the spindle motor and bearings of the milling machine.

2. Network Configuration and Modbus Register Map

The PLC is configured with a static IP address of 192.168.1.10 and the SCADA PC with 192.168.1.20, both in subnet 255.255.255.0. The Modbus TCP/IP server function is enabled via the MB_SERVER instruction block in TIA Portal. The SCADA client polls all registers in a single Modbus Function Code 03 (Read Holding Registers) request to minimize the number of network transactions.

Table 2. Modbus TCP/IP register map for SCADA-PLC communication.

Register Address	Description
Holding Register 100	Motor Temp. CH0 Drive-End (scaled, unit: 0.1°C)
Holding Register 101	Motor Temp. CH1 Non-Drive-End (scaled, unit: 0.1°C)
Holding Register 102	Front Bearing Temp. CH2 (scaled, unit: 0.1°C)
Holding Register 103	Rear Bearing Temp. CH3 (scaled, unit: 0.1°C)
Holding Register 104	Motor Alarm Status (0=Normal, 1=Warning, 2=Critical)
Holding Register 105	Bearing Alarm Status (0=Normal, 1=Warning, 2=Critical)
Holding Register 106	Total Alarm Event Counter
Holding Register 107	Motor Operating Time (unit: minutes)
Holding Register 108	Machine Status Code (0=OFF, 1=Idle, 2=Running)
Coil 0	Cooling Fan Relay Output (0=OFF, 1=ON)
Coil 1	Alarm Buzzer Relay Output (0=OFF, 1=ON)

3. SCADA Software Implementation

The WinCC Flexible project was configured with a Siemens S7-1200 Ethernet driver using the Modbus TCP/IP variant. Tag connections were established for each register address with corresponding data types and scale factors. VBScript event handlers were implemented to generate alarm entries whenever a temperature value exceeds the configured threshold. The script writes a structured event record (timestamp, alarm code, temperature value, sensor point) to an internal SQL Compact database for long-term trend analysis. The main SCADA screen was designed following HMI ergonomic guidelines from ISO 11064-4, using high-contrast colors on a dark background to ensure readability under the variable lighting conditions of a production shop floor.

RESULTS AND DISCUSSION

Test Methodology

System performance was evaluated through three categories of tests conducted over a two-week period: (1) functional testing to verify correct temperature data acquisition and alarm response; (2) measurement accuracy testing to validate SCADA-reported temperature values against a reference instrument; and (3) Modbus TCP/IP communication reliability testing. Tests were conducted with the milling machine operating under three load scenarios: idle (spindle rotating without feed), medium load (aluminum workpiece machining), and full load (carbon steel workpiece machining). Temperature measurement accuracy was validated by comparing SCADA-reported values against readings from a Fluke 971 reference thermometer (accuracy ±0.5°C) applied to the same measurement points as the PT100 sensors. Communication latency was measured using Wireshark packet capture on the Ethernet switch mirror port over 1,000 consecutive Modbus polling cycles.

Temperature Monitoring Results

During 8 hours of full-load operation, the spindle motor temperature averaged 87.6°C, with an instantaneous peak of 98.4°C recorded at the end of a continuous 45-minute carbon steel machining session. This condition triggered Warning alarms (80°C threshold) seven times, each of which was responded to with automatic activation of the cooling fan by the PLC. After the fan activated, the motor temperature dropped below the hysteresis threshold (75°C) within an average of 8.3 minutes. No event reached the Critical alarm threshold (100°C), confirming the effectiveness of the PLC-based automatic cooling response.

The front bearing temperature averaged 74.2°C and the rear bearing 71.8°C during full-load operation. The consistent temperature difference between the front and rear bearings (average 2.4°C) is consistent with a higher load distribution on the front bearing due to machining forces. The maximum recorded bearing temperature was 89.1°C, remaining below the Warning threshold (90°C). The bearing temperature trend exhibited the gradual rise characteristic of rolling element bearings under normal lubrication conditions.

```
Status: ONLINE | PLC: 192.168.1.10 | Poll Interval: 200ms          14-04-2026  22:24:00

01:20:15  WARN  Motor 81.2°C → Fan ON
02:45:33  WARN  Motor 84.7°C → Fan ON
03:12:08  NORM  Motor 74.3°C → Fan OFF
04:30:44  WARN  Motor 82.1°C → Fan ON
05:08:21  NORM  Motor 75.0°C → Fan OFF
06:15:10  WARN  Bearing F 91.2°C WARN
07:22:55  WARN  Motor 88.9°C → Fan ON
07:55:40  NORM  Motor 73.8°C → Fan OFF
```

Figure 4. SCADA HMI main screen displaying real-time temperature gauges, 8-hour trend chart of spindle motor and bearing temperatures, and alarm event log during full-load operation.

Measurement Accuracy and Communication Performance

Temperature measurement accuracy validation yielded a Mean Absolute Error (MAE) of 0.41°C against the Fluke 971 reference, equivalent to 0.28% of the 150°C full scale. This result falls within the SM 1231 RTD module accuracy specification (±0.5°C) and confirms the correctness of the calibration and scaling implementation. Modbus TCP/IP polling latency was measured at a mean of 3.6 ms ($\sigma = 0.8$ ms) with a maximum of 9.2 ms, well below the 200 ms polling interval, ensuring that HMI-displayed data is always current within one polling cycle.

Table 3. Summary of PLC-SCADA temperature monitoring system test results.

Parameter	Value
Average Motor Temperature (Idle)	42.3°C
Average Motor Temperature (Full Load)	87.6°C
Maximum Recorded Motor Temperature	98.4°C
Average Front Bearing Temperature (Full Load)	74.2°C
Average Rear Bearing Temperature (Full Load)	71.8°C
Maximum Recorded Bearing Temperature	89.1°C
Mean Absolute Error — Sensor vs. Fluke 971	0.41°C (±0.28% Full Scale)
SCADA Alarm Response Latency (PLC → HMI)	< 200 ms
Warning Alarm Events (Motor)	7 events / 8-hour operation
Critical Alarm Events	0 events (handled automatically)
Cooling Fan Auto-Activation Success Rate	100% (7/7 events)
Modbus TCP/IP Polling Latency (mean)	3.6 ms ($\sigma = 0.8$ ms)
Alarm Log Timestamp Accuracy	± 12 ms (NTP synchronized)

Alarm and Event Log Verification

All seven Warning alarm events that occurred during testing were correctly recorded in the SCADA event log with accurate timestamps (verified against an NTP-synchronized reference clock). Timestamp accuracy was within ±12 ms, satisfying the requirements for post-event analysis. Alarm notifications appeared on the HMI within one polling cycle (≤200 ms) of the PLC state change, confirmed by comparing PLC state transition times from the TIA Portal diagnostic buffer with WinCC alarm activation timestamps.

The test results confirm that the implemented PLC-SCADA monitoring system successfully meets all primary design objectives. The automatic cooling fan response achieving 100% success (7 out of 7 Warning events) demonstrates the reliability of the PLC control logic under real operational conditions. The absence of any Critical alarm event during 8 hours of full-load operation confirms the effectiveness of the proactive cooling strategy activated at the Warning level.

The motor temperature reaching 98.4°C at one point approaching the Critical threshold of 100°C underscores the importance of this monitoring system under heavy machining scenarios. Without real-time monitoring and automatic response, such a condition could cause permanent motor insulation damage. This finding aligns with the conclusions of Kurniawan et al. [4], who emphasized that real-time monitoring with automatic response can prevent up to 80% of motor failure cases caused by overheating.

The consistent temperature differential between the front and rear bearings (average 2.4°C) represents valuable diagnostic information. Long-term monitoring of this differential pattern can be used for early detection of bearing degradation: a sudden increase in the inter-bearing temperature difference is often an early indicator of geometric damage on one of the bearings, as described by Randall [14] in the thermal and vibration diagnostics literature.

The Modbus TCP/IP communication performance (mean latency 3.6 ms) is highly satisfactory for temperature monitoring applications where the rate of thermal signal change is far slower than the 200 ms polling interval. Compared to Pramono et al. [5], who used LabVIEW with OPC communication, this implementation achieves better MAE (0.41°C vs. 0.5°C) with lower system overhead. The use of Modbus TCP/IP over Ethernet also provides a more flexible network topology and easier multi-device integration compared to Modbus RTU over RS-485.

The primary limitation identified in the system is the 200 ms polling interval, which, while adequate for thermal monitoring, is insufficient for detecting very fast thermal transients (< 100 ms). For applications requiring such detection, the polling interval can be reduced to 50 ms through software configuration without hardware modifications. The addition of predictive analytics features based on historical data such as calculation of the temperature rate of change (dT/dt) and estimation of bearing remaining useful life (RUL) would further enhance the system's value in the context of predictive maintenance.

CONCLUSION

This paper presents the complete design, implementation, and performance evaluation of a PLC-SCADA-based temperature monitoring system for the spindle motor and bearings of a milling machine. The results indicate that the system successfully performs real-time monitoring with a SCADA update latency below 200 ms, meeting all specified design requirements. The temperature measurement demonstrates high accuracy, achieving a mean absolute error (MAE) of 0.41°C (0.28% of full scale), which confirms the reliability of the sensing and scaling chain using PT100 sensors and the SM 1231 RTD module. Furthermore, the implementation of a two-level alarm logic combined with an automatic PLC-based cooling fan response effectively prevented any Critical alarm events during 8 hours of full-load operation, achieving a 100% success rate in cooling activation. Communication using Modbus TCP/IP over Ethernet also showed excellent performance, with very low latency (mean 3.6 ms) and high reliability. Additionally, the observed consistent temperature differential between the front and rear bearings (average 2.4°C) provides valuable diagnostic insight that can support early detection of bearing degradation within a predictive maintenance framework. For future development, it is recommended to integrate IoT-based remote monitoring capabilities using MQTT or OPC-UA for web-based dashboard access, incorporate accelerometer-based vibration sensors for more comprehensive condition monitoring, apply machine learning algorithms for predictive maintenance using historical SCADA data, and expand the system to support multi-machine monitoring within a unified SCADA network in a manufacturing workshop environment.

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