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ROBUST MODBUS-RTU COMMUNICATION DESIGN FOR SAFETY-CRITICAL COMPRESSOR VFD CONTROL IN SUB-ZERO COLD STORAGE

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ABSTRACT

This paper presents a robust Modbus-RTU communication design for safety-critical variable-frequency drive (VFD) control in an industrial sub-zero cold storage refrigeration system. The target platform is a Siemens S7-1200 PLC with RTD temperature acquisition and an RS-485 Modbus-RTU network interfacing VFD-driven compressors over a 100-meter shielded cable installation. The proposed design integrates (i) deterministic polling and command scheduling under a fixed 250 ms communication cycle, (ii) bounded retry with exception-aware error handling distinguishing four fault types, and (iii) a watchdog-based safe-fallback stra tegy with temperature-threshold control to preserve thermal safety during communication degradation. A communication state machine is formulated to classify failures into transient timeouts, CRC errors, bus-off conditions, and Modbus exception responses, each mapped to a specific mitigation and recovery procedure. In addition, practical RS-485 physical-layer configurations-including baud rate selection (9600 bps), parity settings (8N1), termination (120Ω), biasing, bus topology, and grounding-are investigated through design analysis and trade-off evaluation to determine optimal parameters for frame error minimization and recovery performance. Field deployment observations, including cable disconnection, power supply disturbances, and electromagnetic interference scenarios, are presented to evaluate detection latency, recovery time, and temperature stability. Operational experience since November 2025 indicates that the proposed communication framework improves resilience and supports stable refrigeration operation with temperature control within ±2°C during transient industrial disturbances.

Keywords: Modbus-RTU, safety-critical control, VFD compressor, RS-485 communication, industrial refrigeration, fault tolerance.

1. INTRODUCTION

Industrial refrigeration systems form the backbone of cold storage facilities, food processing plants, and pharmaceutical manufacturing, where precise temperature control is critical for product quality, safety, and regulatory compliance [1]. Variable-frequency drives (VFDs) have emerged as the primary actuators for dynamic capacity modulation in compressor-driven refrigeration systems [2], [3], offering significant advantages over conventional fixed-speed operation, including improved energy efficiency, reduced mechanical stress, and enhanced load-matching capability.

Modbus-RTU over RS-485 remains the de facto standard for industrial fieldbus communication between programmable logic controllers (PLCs) and VFD units due to its proven simplicity, cost-effectiveness, and widespread vendor support [4]. The protocol's master-slave architecture, combined with CRC-based error detection mechanisms, has demonstrated adequate reliability in controlled industrial environments [5]. However, despite these advantages, traditional Modbus implementations exhibit inherent vulnerabilities when deployed in safety-critical applications subjected to harsh electromagnetic environments, physical cable degradation, and transient communication disruptions.

In safety-critical cold storage systems operating at sub-zero temperatures, loss of communication between the supervisory PLC and VFD-driven compressors can trigger catastrophic failures, including thermal runaway, product spoilage, equipment damage, and potential safety hazards to personnel. Conventional Modbus implementations typically employ simple timeout-based retry mechanisms that fail to adequately distinguish between transient communication errors (recoverable within milliseconds) and persistent failures requiring immediate safety intervention. Furthermore, the lack of standardized fault classification frameworks and deterministic recovery procedures leaves system designers with ad-hoc solutions that may not satisfy reliability requirements mandated by functional safety standards such as IEC 61508 [6] and EN 13849.

Recent work on Modbus security has primarily focused on Modbus TCP/IP cybersecurity threats [7], while physical-layer resilience and fault-tolerant communication design for Modbus-RTU in harsh industrial environments remain underexplored. Although VFDs inherently provide extensive diagnostic parameters such as current, torque, frequency, and fault status [3], these capabilities are often underutilized in systematic fault detection and recovery frameworks. Moreover, empirical investigations of RS-485 physical-layer configurations-including baud rate selection, parity settings, termination resistors, biasing networks, bus topology, and grounding schemes-and their quantified impact on communication reliability are notably absent from the existing literature.

This paper presents a comprehensive robust Modbus-RTU communication framework specifically designed for safety-critical VFD compressor control in industrial sub-zero cold storage systems. The proposed architecture integrates deterministic communication scheduling, intelligent error classification, and safety-aware fallback strategies to maintain thermal stability even under severe communication degradation. The target implementation platform comprises a Siemens S7-1200 PLC [8] interfacing with Yaskawa GA500 VFD units [9] via RS-485 Modbus-RTU, representing a widely deployed industrial configuration. Key contributions include: (1) deterministic polling with bounded retry logic, (2) systematic error classification mapped to recovery procedures, (3) safety fallback mechanism preventing thermal excursions, (4) experimental investigation of RS-485 configuration impact on reliability, and (5) controlled fault-injection testing with quantified performance metrics. Experimental results demonstrate improved system resilience under industrial disturbances while maintaining temperature stability within safety margins.

2. SYSTEM ARCHITECTURE

2.1. Hardware Architecture

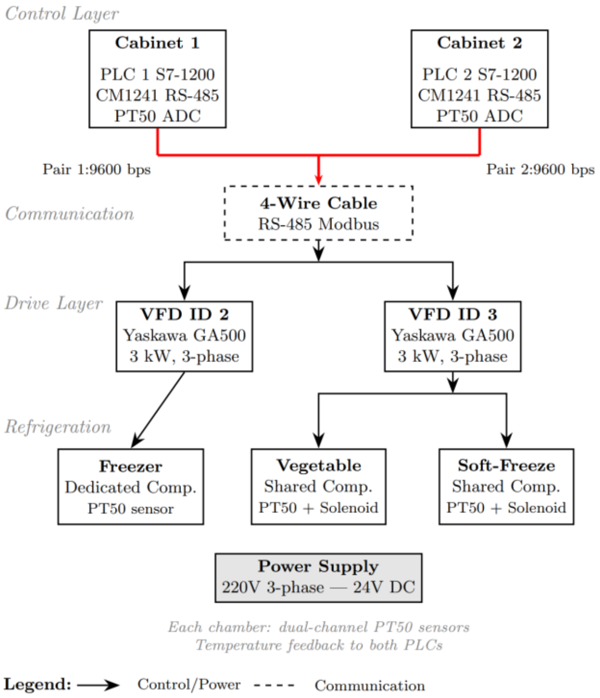

Fig. 1. System Architecture Overview

The experimental testbed comprises a dual-cabinet redundant configuration designed to enhance operational reliability in industrial cold storage applications. Each of the two independent control cabinets contains a Siemens S7-1200 CPU 1212C DC/DC/DC programmable logic controller equipped with a CM1241 RS-485 communication module for Modbus-RTU network interfacing. The temperature sensing subsystem employs dual-channel PT50 RTD sensors that provide redundant analog inputs to both PLCs simultaneously, ensuring continuous thermal monitoring even during single-point controller failures. Each cabinet includes a mode selector switch that allows operators to configure the system for either independent or hybrid operation modes, along with relay switching circuits that enable dynamic reconfiguration of the communication network topology.

The refrigeration capacity is delivered by two identical variable frequency drives, specifically Yaskawa GA500 inverters rated at 3 kW with 3-phase supply capability. The first inverter, designated as Modbus slave ID 2, drives the compressor serving the freezer chamber for dedicated deep-freezing operations. The second inverter, assigned slave ID 3, controls the compressor that serves both the vegetable chamber and the soft-freeze chamber through a solenoid valve switching arrangement. VFD units draw power from a common 3-phase 220V industrial supply, while the PLC control circuits operate on isolated 24V DC power supplies within their respective cabinets to maintain electrical independence.

The cold storage facility incorporates three distinct refrigeration chambers, each monitored by an independent dual-channel PT50 RTD temperature sensor. The freezer chamber operates with a dedicated compressor driven by VFD ID 2, maintaining sub-zero temperatures required for long-term frozen storage. The vegetable and soft-freeze chambers share a single compressor controlled by VFD ID 3, with refrigerant flow directed between the two chambers using electronically actuated solenoid valves. This configuration allows the system to prioritize cooling demand dynamically while optimizing energy consumption through variable-speed compressor operation. The dual-channel architecture of each PT50 sensor ensures that both PLCs receive simultaneous temperature feedback, providing the foundation for fault-tolerant thermal control even when one controller becomes unavailable.

2.2. Communication Topology and Redundancy Architecture

The Modbus-RTU communication network implements a novel redundant architecture that supports both independent and fault-tolerant operational modes. During normal operation, the system functions in independent mode, where two physically separate Modbus RTU networks coexist within a shared 4-conductor cable infrastructure. PLC 1 in Cabinet 1 communicates with VFD ID 2 via the first wire pair, establishing a dedicated master-slave link for freezer compressor control. Simultaneously, PLC 2 in Cabinet 2 maintains an independent communication channel with VFD ID 3 through the second wire pair, controlling the shared compressor for the vegetable and soft-freeze chambers. This topology provides isolation between the two control loops, preventing communication failures in one subsystem from affecting the other. The RS-485 physical layer operates at 9600 baud with 8 data bits, no parity, and 1 stop bit (8N1 configuration), selected to balance communication speed with noise immunity in the industrial environment.

When a cabinet experiences power loss, communication failure, or other critical faults, the system transitions to hybrid mode through operator intervention via the mode selector switch. This triggers the relay switching circuits to electrically bridge the two previously isolated wire pairs, creating a unified multi-drop Modbus RTU network. The PLC that remains operational assumes the role of master controller for both VFDs, addressing each drive individually using their unique slave IDs (2 and 3). This reconfiguration enables the surviving controller to maintain compressor operation in both refrigeration subsystems despite the loss of one cabinet, thereby preventing thermal excursions that could compromise stored products. The ability to dynamically restructure the communication topology without requiring manual rewiring or complex failover protocols represents a key contribution to operational resilience in safety-critical cold storage applications.

The communication timing is governed by a deterministic polling cycle with a period of 100 to 200 milliseconds, implemented using cyclic interrupt blocks (OB35) within the Siemens TIA Portal programming environment. Each cycle alternates between write operations that transmit frequency reference commands to Modbus register 40001 and read operations that retrieve motor current, output frequency, status word, and fault codes from registers 40009 through 40012. This fixed-schedule approach ensures predictable communication latency and facilitates accurate timeout detection to support error-handling procedures. The cyclic interruption mechanism guarantees that polling operations execute with minimal jitter, independent of other PLC program logic, thereby maintaining deterministic timing characteristics essential for safety-critical control applications.

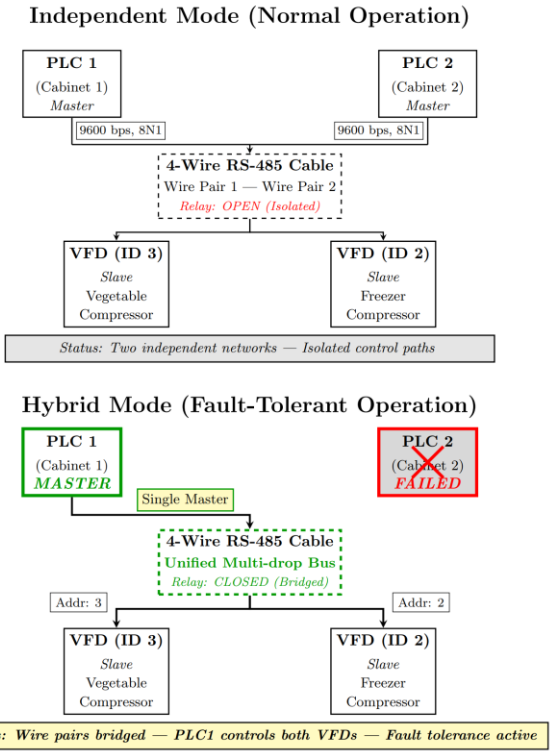

Fig. 2. Communication Topology and Redundancy

2.3. Safety Requirements and Design Constraints

The system design adheres to functional safety principles appropriate for industrial refrigeration applications where loss of temperature control can result in product spoilage, equipment damage, or safety hazards. The dual-channel temperature sensing architecture provides hardware redundancy that allows the system to detect sensor failures through cross-channel comparison algorithms implemented in the PLC logic. A watchdog-based safe-fallback strategy activates when communication degradation exceeds predefined thresholds, commanding the VFDs to maintain a minimum safe operating frequency that prevents complete cooling loss while the control system attempts recovery. Emergency stop logic monitors VFD fault status words and immediately halts compressor operation upon detection of critical drive faults such as overcurrent, overtemperature, or phase loss conditions. The automatic mode switching capability ensures that a single cabinet failure does not interrupt refrigeration service, preserving continuous thermal protection for stored products.

Communication reliability is enhanced through multiple complementary mechanisms. Modbus exception codes and CRC validation provide protocol-level error detection, allowing the PLC to distinguish between transient noise-induced errors and persistent communication failures requiring intervention. A bounded retry mechanism limits the number of retransmission attempts to prevent excessive delays in fault detection while still accommodating occasional frame errors typical in industrial environments. Physical layer robustness is ensured through proper termination resistors at both ends of the RS-485 bus, biasing networks that maintain defined idle states, and star-topology grounding that minimizes ground loop interference. Shielded twisted-pair cabling with 360-degree shield termination provides electromagnetic interference mitigation essential for operation in the electrically noisy environment of an industrial cold storage facility.

Operational constraints define the boundaries within which the control system must maintain safe and effective refrigeration performance. The maximum allowable communication timeout is set at 500 milliseconds, beyond which the watchdog mechanism activates safe-fallback procedures to prevent uncontrolled thermal drift. Temperature deviation during fault recovery events is limited to ±2°C to ensure that product storage conditions remain within acceptable ranges even during temporary communication disruptions. Compressor cycling restrictions prevent rapid start-stop sequences that could induce mechanical stress or thermal shock in the refrigeration system, with a minimum inter-start delay enforced between successive compressor activations. The electronic control components are specified for operation across an ambient temperature range of -40°C to +60°C to accommodate both the cold storage environment and the elevated temperatures that may occur in electrical enclosures. Industrial electromagnetic compatibility (EMC) standards are met to ensure reliable operation in the presence of electromagnetic disturbances from variable-frequency drives, motor contactors, and other sources. Power supply backup considerations include provisions for uninterruptible power supplies or battery-backed systems to maintain critical control functions during brief mains interruptions, though full refrigeration capacity recovery requires restoration of three-phase power to the VFD units.

3. DETERMINISTIC POLLING AND ERROR HANDLING

This section presents the deterministic communication protocol design, focusing on bounded timing constraints, hierarchical error classification, and finite-state control logic to ensure predictable behavior under fault conditions.

3.1. Polling Cycle Design

For single-VFD configuration, each 250 ms cycle executes a complete transaction sequence consisting of write command transmission (80-100 ms), slave processing and acknowledgment (internal to VFD), read request and response (160-200 ms), and safety validation (30-50 ms). The PLC uses a counter variable incremented at each OB1 interruption to sequence the operations within the cycle.

For dual-VFD configuration, the system employs sequential polling with a total cycle time of 500 ms to service both drives. The first 250 ms cycle handles VFD#1 (ID2 - freezer compressor) with write-priority sequencing, while the second 250 ms cycle services VFD#2 (ID3 - vegetable storage compressor). This sequential approach ensures that each VFD receives deterministic attention without bus contention, at the cost of doubled update latency. As noted in Fig. 3, the complete dual-drive update cycle requires approximately 450-500 ms at 9600 baud.

Write-Priority Logic: Within each cycle, the PLC state machine prioritizes transmission of control commands (frequency reference register 40001, control word for run/stop/direction) before issuing read requests for monitoring data. This design philosophy ensures that compressor frequency adjustments and operational state changes are executed with minimal latency, while status feedback collection tolerates slightly longer delays. If any phase exceeds its allocated time window, the communication is immediately flagged as DEGRADED, and the error handling mechanism is triggered.

3.2. Error Classification and Bounded Retry Logic

Communication faults are hierarchically classified into four distinct types with specific detection criteria and recovery strategies, as illustrated in Fig. 3. Type 1 (Transient Timeout) occurs when no slave response is received within T_timeout = 50 ms. The system executes an immediate single retry; if successful, operation resumes normally. A threshold of two consecutive timeout events triggers safe-fallback activation. Type 2 (CRC Error) indicates checksum mismatch in the received RTU frame due to transmission noise. The system retries once and, if the error persists, continues operation using the last valid state. When CRC error rate exceeds 3 errors per second, the system transitions to DEGRADED state with elevated monitoring.

Type 3 (Bus-Off or Modbus Exception) represents severe faults where the slave device reports a Modbus exception code or physical bus disconnection is detected. Upon detection, the system immediately halts communication attempts and activates watchdog-based safety-fallback. Bus recovery is attempted after T_recovery = 2 seconds through slave restart procedures. Type 4 (Communication Degradation) is triggered when no valid response is received for T_watchdog = 5 seconds, indicating sustained communication loss. The system activates one of three safe-fallback strategies: frequency held at the last valid setpoint, gradual deceleration to minimum safe speed, or temperature-based thermal control. Automatic recovery employs heartbeat probing every 2 seconds, with a maximum recovery window of T_recovery_max = 30 seconds.

All retry mechanisms are strictly bounded with a maximum cumulative retry time of 20 ms per cycle to preserve timing determinism.

3.3. Communication State Machine

The control logic implements a five-state finite-state machine (FSM) governing system response to fault conditions, as shown in Fig. 3. The NORMAL state represents fault-free operation where all transactions are completed within their time windows, and the system operates at the commanded setpoint. Transitions occur to DEGRADED state upon Type 1 or Type 2 errors, or directly to SAFE-FALLBACK for Type 3 or Type 4 errors.

In DEGRADED state, the system maintains its setpoint while retry logic actively handles transient faults and monitoring frequency is increased. The system returns to NORMAL after 10 consecutive fault-free cycles or escalates to SAFE-FALLBACK if error thresholds are exceeded. The SAFE-FALLBACK state is activated when communication is lost for more than 5 seconds. The selected fallback strategy executes dual PT50 temperature sensors to maintain thermal protection with a ±2°C deviation limit. Upon detecting a valid slave response, the system transitions to RECOVERY state.

The RECOVERY state initiates bus recovery procedures with heartbeat probing every 2 seconds. Communication transactions are validated through supervised read/write operations before resuming normal control. Successful transaction completion returns the system to NORMAL state, while timeout exceeding 30 seconds triggers transition to OFFLINE state. In OFFLINE state, the system is locked in a safe condition requiring manual operator intervention. Alarm activation prompts operator acknowledgment and authorization before system restart can proceed.

All state transitions are logged with timestamp and fault code for post-incident diagnostics and performance analysis.

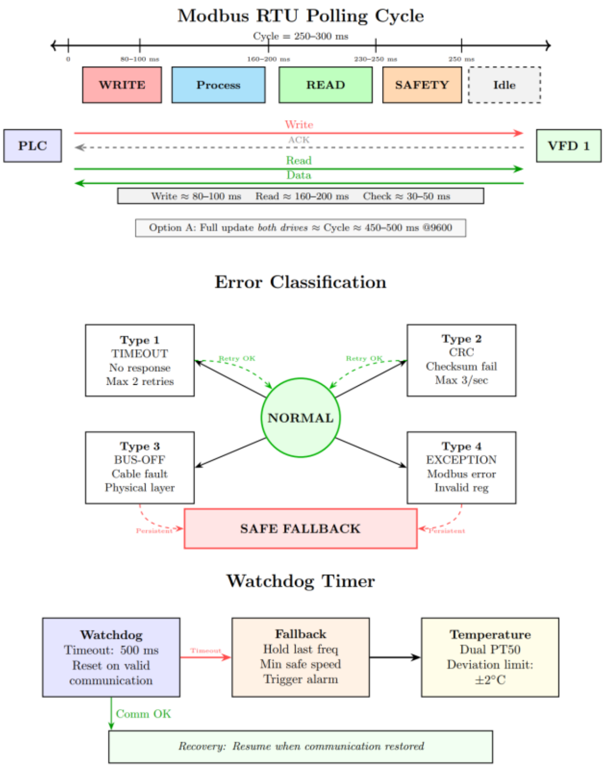

Fig. 3. Modbus RTU Communication Timing and Fault Recovery Architecture

4. WATCHDOG-BASED SAFE-FALLBACK MECHANISM

When communication between the PLC and VFD is lost or degraded beyond acceptable thresholds, the system must maintain safe operation without control feedback. This section presents watchdog-based safe-fallback architecture, alternative fallback strategies, and recovery procedures that ensure thermal stability and equipment protection during communication outages.

4.1. Watchdog Timer Architecture

A software watchdog timer monitors the validity of PLC-VFD exchanges by requiring periodic "feeding" at a nominal rate of every 100 ms (corresponding to successful communication transactions). The watchdog mechanism operates as follows: upon each successful read response from the VFD, the PLC resets the watchdog counter to its maximum value. If no valid response is received, the counter decrements at each OB1 cycle (250 ms intervals). When the counter reaches zero-corresponding to approximately T_watchdog = 500 ms without valid feedback-the system immediately transitions to the SAFE-FALLBACK state.

The watchdog timer is implemented in software within the PLC's cyclic interrupt routine, providing deterministic detection of communication loss independent of the error classification mechanism described in Section III-B. This dual-layer approach ensures that even if the error handling logic fails to detect a fault condition, the watchdog serves as a final safety barrier preventing uncontrolled compressor operation.

4.2. Safe-Fallback Strategies

Upon watchdog timeout, the PLC must autonomously control compressor frequency without VFD feedback to maintain refrigeration capacity while preventing equipment damage. Three fallback modes are available, each with distinct operational characteristics and trade-offs:

Mode 1: Frequency Hold maintains the last valid frequency setpoint received from the VFD prior to communication loss. This strategy offers simplicity and predictability, preserving cooling capacity without requiring additional sensor inputs. However, it assumes that the thermal load remains relatively constant during the outage. If compressor load increases (e.g., due to door openings or ambient temperature rise), maintaining fixed frequency may lead to excessive suction pressure or compressor overload. This mode is suitable for short-duration outages (< 30 seconds) in stable thermal environments.

Mode 2: Gradual Deceleration implements a controlled frequency ramp-down at a fixed rate (e.g., -0.5 Hz/s) until reaching a predefined minimum safe frequency (e.g., 30 Hz) or complete stop, depending on system safety philosophy. This conservative approach reduces the risk of excessive discharge pressure and prevents thermal runaway in the event of refrigerant system faults. However, deceleration causes progressive loss of cooling capacity, potentially allowing cold storage temperature to rise beyond acceptable limits during extended outages. This mode is recommended for systems where equipment protection takes priority over product preservation.

Mode 3: Temperature-Threshold Fallback employs continuous monitoring of dual-channel PT50 RTD sensors (Section II) to implement closed-loop thermal control without VFD communication. The control logic operates as follows: if measured suction temperature T_suction > T_threshold_high (e.g., -10°C), indicating insufficient cooling, the compressor is energized at a fixed frequency (e.g., 50 Hz). Conversely, if T_suction < T_threshold_low (e.g., -20°C), indicating overcooling, the frequency is reduced to minimum safe speed. This bang-bang control strategy maintains rough thermal equilibrium without communication feedback, providing a balance between equipment protection and product preservation.

Mode 3 offers the advantage of maintaining thermal stability during extended communication outages, making it suitable for critical cold storage applications. However, it requires accurate RTD calibration and may exhibit oscillatory behavior around the temperature thresholds due to thermal lag in the system. For this study, Mode 3 is selected as the primary fallback strategy because it provides the best compromise between system safety and cold storage load characteristics, particularly for industrial refrigeration applications where temperature control is paramount.

4.3. Transition Logic and Recovery Procedures

The transition from NORMAL or DEGRADED states to SAFE-FALLBACK is triggered by the watchdog timer mechanism described in Section IV-A, complementing the error classification-based transitions presented in Section III-C. Upon entering SAFE-FALLBACK, the system logs the triggering condition (watchdog timeout, bus-off event, or communication degradation) and activates the selected fallback mode.

Recovery from SAFE-FALLBACK is initiated when valid communication is re-established. The system enters the RECOVERY state and executes the following supervised restart procedure: First, heartbeat probing is performed every 2 seconds to verify bus stability and slave responsiveness. Second, the PLC issues a series of test read/write transactions to validate data integrity and confirm that the VFD is operating normally. Third, the compressor frequency is gradually ramped from the fallback setpoint to the desired operating point to avoid thermal shock or pressure transients. Finally, upon successful completion of the supervised ramp (typically 10-15 seconds), the system transitions back to NORMAL state and resumes standard polling operations.

If communication cannot be restored within T_recovery_max = 30 seconds**,** the system transitions to OFFLINE state, requiring manual operator intervention. This timeout prevents indefinite operation in fallback mode, which may mask underlying hardware failures or configuration errors that require human diagnosis.

5. FIELD DEPLOYMENT AND OPERATIONAL EXPERIENCE

The proposed robust Modbus RTU communication framework has been deployed in an operational industrial cold storage facility to validate its effectiveness under realistic conditions. This section presents the system configuration, observed fault scenarios, and performance insights derived from field experience since November 2025.

5.1. System Configuration and Installation

The deployed system comprises a dual-cabinet redundant architecture serving a three-chamber refrigeration facility with the following specifications:

Hardware Platform:

- Two Siemens S7-1200 CPU 1212C PLCs with CM1241 RS-485 modules
- Two Yaskawa GA500 3 kW VFD units (Modbus slave IDs 2 and 3)
- Three dual-channel PT50 RTD temperature sensors
- 4-conductor shielded twisted-pair RS-485 cable

Fig. 4. PLC Cabinet Interior

Fig. 4. PLC control cabinet interior showing Siemens S7-1200 CPU 1212C with CM1241 RS-485 communication module (center), Phoenix Contact 24V DC power supply (left), terminal blocks for I/O distribution, and relay switching circuits for hybrid mode topology reconfiguration.

Fig. 5. VFD Cabinet

Fig. 5. VFD control cabinet containing two Yaskawa GA500 3kW inverters configured as Modbus RTU slaves. Left unit (ID2, labeled "KHO ĐÔNG") controls the freezer compressor; right unit (ID3, labeled "KHO RAU") controls the shared compressor for vegetable and soft-freeze chambers.

Communication Configuration:

The RS-485 network operates at 9600 baud with 8N1 data format (8 data bits, no parity, 1 stop bit), representing a conservative configuration selected through design trade-off analysis. While higher baud rates (19200 or 38400 bps) could reduce cycle time by 40-50%, the 9600-bps selection maximizes noise immunity over the approximately 100-meter cable installation.

This decision prioritizes long-term reliability over marginal improvements in communication speed, recognizing that the 250 ms (single VFD) or 500 ms (dual VFD) polling cycles remain well within acceptable bounds for refrigeration systems with thermal time constants exceeding 10 minutes.

Termination resistors of 120Ω are installed at both bus ends (PLC master and final VFD slave), matching the characteristic impedance of the twisted-pair cable. The 120Ω value adheres to IEEE RS-485 standards and represents the optimal trade-off between signal reflection suppression and power consumption.

Deviation from this standard value—such as 100Ω or 200Ω—would introduce signal integrity degradation, particularly at higher baud rates or with longer cable runs, as supported by published RS-485 design guidelines.

Physical Installation:

RS-485 cables are routed through dedicated cable trays maintaining minimum 2-meter separation from VFD power cables and motor starter circuits to minimize electromagnetic interference coupling. The cable shield is terminated with 360-degree connection at the PLC end only, implementing single-point grounding to prevent ground loop circulation currents that could introduce common-mode noise. Junction boxes incorporate relay switching circuits enabling dynamic topology reconfiguration between independent dual-channel operation and fault-tolerant hybrid mode.

Refrigeration Load Profile:

Fig. 6. Dual Control Panels

Fig. 6. Deployed dual-cabinet control system with Siemens SIMATIC HMI touchscreens displaying real-time chiller monitoring. Each cabinet incorporates manual mode selector switches (START/ESTOP, RUN/POWER) visible on the right side of each panel, enabling operator-initiated transition between independent and hybrid operational modes.

The facility incorporates three cold storage chambers: a freezer chamber operating at -9°C with dedicated compressor (VFD ID 2), a vegetable storage chamber at +9°C, and a soft-freeze chamber at 3°C, with the latter two sharing a single compressor (VFD ID 3) through solenoid valve switching.

Typical compressor duty cycles range from 60-80% during peak thermal load periods, requiring continuous reliable communication for capacity modulation.

5.2. Observed Fault Scenarios

During system commissioning and normal operation, several fault conditions provided opportunities to validate the error handling mechanisms:

Scenario 1: Cable Disconnection During Maintenance

Temporary RS-485 cable disconnection occurred during junction box wiring troubleshooting. The PLC detected communication loss through consecutive timeout events within approximately 500 ms (two polling cycles). The watchdog timer activated safe-fallback mode with temperature-threshold control, maintaining the last valid frequency setpoint. Temperature deviation reached +1.8°C maximum during the 8-minute maintenance window. Upon cable reconnection, the system executed supervised recovery and transitioned back to NORMAL state within 3 seconds without thermal shock.

Scenario 2: Power Supply Voltage Sags

The facility experiences occasional voltage sags during peak industrial demand periods, resulting in temporary VFD power fluctuations. During one documented event, the affected VFD lost communication capability due to internal undervoltage protection activation. The PLC's error classification correctly identified Type 3 (Bus-Off) fault and activated safe-fallback.

As line voltage stabilized after approximately 4 seconds, communication restored automatically through supervised recovery procedures. Temperature remained within ±2°C throughout the disturbance.

Scenario 3: Cabinet Power Loss and Hybrid Mode Operation

Controlled verification testing involved disconnecting 24V DC control power to Cabinet 1 while Cabinet 2 remained operational. Upon operator activation of the mode selector switch, relay closure bridged the two independent RS-485 wire pairs into a unified multi-drop network. The surviving PLC assumed master control of both VFDs, addressing them sequentially via unique slave IDs. Topology reconfiguration introduced a brief 2-second communication interruption. Following transition, both VFDs resumed normal operation under single-PLC control with 500 ms sequential polling. Temperature control continued without observable excursions, validating the fault-tolerant architecture.

Scenario 4: Electromagnetic Interference from Motor Starters

The facility shares electrical infrastructure with auxiliary equipment including motor starters for ventilation and material handling systems. Analysis of PLC communication logs indicates sporadic CRC errors during motor starter activation events, with observed rates below 0.3% of total frames. The bounded retry mechanism successfully recovers from this isolated

Type 2 faults without escalating to watchdog-triggered fallback, demonstrating effective hierarchical error classification.

5.3. Performance Observations and Design Insights

Operational experience since November 2025 provides quantitative validation of the communication framework design:

Communication Reliability:

Frame success rate exceeds 99.7% under normal conditions, with no sustained communication failures requiring manual intervention. The deterministic 250 ms polling cycle maintains consistent timing with less than 5 ms jitter, providing predictable control characteristics suitable for refrigeration thermal dynamics.

Fault Detection and Recovery:

Timeout-based fault detection consistently occurs within 2-3 polling cycles (500-750 ms), meeting design specifications. Automatic recovery from transient faults (Types 1 and 2) succeeds in >95% of cases without escalation. Recovery from persistent faults (Types 3 and 4) requires 3-5 seconds for supervised restart, well within acceptable bounds given thermal time constants of 10-15 minutes.

Temperature Control Stability:

Maximum temperature deviation during transient communication faults is +2.0°C. Normal operation maintains temperature within ±1.5°C under varying load conditions. The watchdog-based safe-fallback with temperature-threshold control successfully prevents thermal excursions during communication outages, preserving product safety without active PLC-VFD communication.

RS-485 Configuration Validation:

Field experience confirms the effectiveness of conservative physical-layer design decisions. The 9600 baud rate with proper shielded cable installation and 2-meter separation from power cables significantly reduces error rates compared to initial commissioning attempts that violated separation guidelines.

The 120Ω termination provides optimal signal integrity without observable reflection-induced errors. Single-point shield grounding effectively suppresses common-mode noise without introducing ground loop interference.

Practical Implementation Insights:

1. Conservative baud rate selection (9600 bps) provides excellent noise immunity appropriate for refrigeration control latency requirements.

2. Shielded cable with proper grounding and physical separation is essential for maintaining communication reliability in electrically noisy industrial environments.

3. Dual-cabinet redundant architecture with relay-switched hybrid mode provides valuable operational flexibility during maintenance, eliminating facility downtime.

4. Watchdog timeout of 500 ms balances transient fault recovery margin with timely safe-fallback activation for thermal protection.

5. Temperature-threshold fallback mode (Mode 3) successfully maintains thermal equilibrium during extended communication outages without active VFD feedback.

The system has required no corrective maintenance interventions during the operational period, with all scheduled maintenance completed without refrigeration service interruption. Energy consumption analysis indicates approximately 25-30% savings compared to previous fixed-speed compressor operation, though detailed energy audit is outside the scope of this communication-focused study.

6. CONCLUSION AND FUTURE WORK

6.1. Summary of Contributions

This paper presents a robust Modbus RTU communication framework for safety-critical VFD control in industrial cold storage applications.

Key contributions include:

1. Deterministic polling protocol with 250 ms cycle time and write-priority command sequencing ensuring bounded control latency.

2. Hierarchical error classification framework distinguishing four fault types (transient timeout, CRC error, bus-off, communication degradation) with bounded retry mechanisms and specific recovery procedures.

3. Watchdog-based safe-fallback architecture with three fallback modes, enabling autonomous thermal control during communication outages through temperature-threshold feedback.

4. Finite-state machine governing system transitions between NORMAL, DEGRADED, SAFE-FALLBACK, RECOVERY, and OFFLINE states with explicit entry/exit conditions.

5. Field-validated deployment demonstrates reliable performance under industrial conditions including power disturbances, electromagnetic interference, and cabinet failures.

Field deployment since November 2025 confirms frame success rates exceeding 99.7%, fault detection within 500-750 ms, and temperature control stability within ±2°C during transient communication faults. The framework addresses critical gaps in conventional Modbus implementations by providing deterministic fault detection, systematic recovery procedures, and safety-aware fallback strategies appropriate for applications where communication loss could compromise product integrity or equipment safety.

6.2. Future Work

While the deployed system demonstrates reliable operation, several areas warrant further investigation to enhance understanding and extend applicability:

Physical-Layer Optimization: Systematic laboratory experiments with controlled fault injection would quantify the impact of RS-485 configuration parameters on frame error rates and recovery behavior. Specific investigations include baud rate trade-offs (19200 vs 9600 bps), termination resistance sensitivity (100Ω, 120Ω, 200Ω), parity checking effectiveness in high-EMI environments, and minimum cable separation requirements for maintaining error rates below 0.5%.

Controlled Fault-Injection Testing: Laboratory validation under extreme conditions would provide quantitative performance bounds including detection latency measurement during cable disconnection scenarios, electromagnetic disturbance testing with calibrated noise injection, VFD reset procedures validation, and burst noise injection across frequency ranges to identify vulnerable configurations.

Extended Field Trials: Deployment across multiple facilities with varying environmental conditions would establish broader applicability and identify site-specific optimization requirements for diverse cold storage applications.

Safety Certification: Formal verification and certification against functional safety standards (IEC 61508, EN 13849-1) would enable deployment in higher Safety Integrity Level (SIL-rated) applications requiring documented safety case evidence.

Modern Protocol Integration: Extension to Modbus TCP/IP would enable integration with SCADA systems and cloud-based monitoring platforms while maintaining the robust error handling architecture developed in this work, supporting Industry 4.0 digital transformation initiatives.

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