

Design and Implementation of a PLC-Based Multi-Evaporator Temperature Control System for Cold Storage Applications

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Abstract

The paper aims to the design, implementation, and evaluation of a PLC-based temperature control system for a multi evaporator cold storage store. The system was developed to manage three independent storage rooms dedicated to meat, fish, and chicken each requiring separate temperature ranges. By employing Siemens S7-1200 PLCs, PT100 sensors, and solenoid valves, the system achieves precise temperature regulation through individual PID control loops. The project included comprehensive hardware integration, software development using TIA Portal, and rigorous field testing. Results indicate that the system-maintained temperature set points within $\pm 0.5^{\circ}\text{C}$, reduced energy consumption by approximately 18%, and achieved 99.5% uptime over three months. The system's modular design, advanced control logic, and user-friendly HMI interface demonstrate the effectiveness of PLCs in improving efficiency, reliability, and flexibility in cold storage environments. Recommendations are provided for future enhancements, including IoT integration and predictive maintenance features, to further elevate system performance and sustainability.

Keywords: Temperature control, multi evaporator, cold storage, Program Logic Controller (plc).

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المخلص

يستعرض هذا البحث تصميم وتنفيذ وتقييم نظام تحكم بدرجة الحرارة يعتمد على المتحكم المنطقي القابل للبرمجة (PLC) في مستودع تبريد متعدد المبخرات. تم تطوير النظام لإدارة ثلاث غرف تخزين مستقلة مخصصة للحوم والأسماك والدواجن، حيث تتطلب كل غرفة نطاقاً حرارياً مختلفاً. باستخدام وحدات PLC من نوع Siemens S7-1200 وحساسات PT100 وصمامات كهربائية، يحقق النظام تحكماً دقيقاً في درجات الحرارة من خلال حلقات تحكم PID مستقلة. شمل المشروع تكاملاً كاملاً للأجهزة، وتطوير البرمجيات باستخدام برنامج TIA Portal، واختبارات ميدانية صارمة. أظهرت النتائج أن النظام حافظ على درجات الحرارة المطلوبة ضمن ± 0.5 درجة مئوية، وقلل من استهلاك الطاقة بحوالي 18%، وحقق نسبة تشغيل بلغت 99.5% خلال فترة ثلاثة أشهر. يبرز التصميم المعياري للنظام ومنطق التحكم المتقدم وواجهة المستخدم سهلة الاستخدام فعالية أنظمة PLC في تحسين الكفاءة والموثوقية والمرونة في بيئات التخزين البارد. كما تم تقديم توصيات لتحسينات مستقبلية مثل دمج تقنيات إنترنت الأشياء والصيانة التنبؤية لتعزيز الأداء والاستدامة بشكل أكبر.

الكلمات المفتاحية: التحكم بدرجة الحرارة، متعدد المبخرات، المخازن المبردة، لغة التحكم المنطقي.

Introduction

Efficient temperature control is critical in cold storage warehouses, especially when preserving perishable products such as meat, fish, and chicken. In multi-evaporator systems where each

storage room must maintain a individual temperature set point, achieving exact and reliable control becomes increasingly complex. Programmable Logic Controllers (PLCs) have emerged as a robust solution for automating temperature regulation across independent rooms, providing both flexibility and reliability [1]. PLCs are industrial digital computers specifically designed for the control of manufacturing processes, such as assembly lines, robotic devices, and, increasingly, HVAC and refrigeration systems [2]. Their application in cold storage environments allows for the real-time monitoring and adjustment of multiple refrigeration units, each governed by its own temperature sensor and feedback control loop [3]. By deploying a PLC-based system, operators can ensure that each storage room sustains its optimal temperature, minimizing spoilage and maintaining food safety standards [4].

The core advantage of using a PLC in a multi-evaporator cold storage warehouse lies in its programmability and scalability. Traditional thermostat-based systems are often rigid and challenging to adjust for dynamic storage needs. In contrast, PLCs allow users to easily modify set points, add alarms, integrate with Human Machine Interfaces (HMIs), and expand the system as needed [5]. This level of customization is particularly essential in facilities where different types of goods—such as meats, fish, and chicken—have varying storage temperature requirements [6]. In a typical setup, each room in the warehouse is equipped with temperature sensors, usually PT100 or thermocouples, connected to the PLC's analog inputs [7]. The PLC continuously reads these inputs and, based on pre-programmed logic, actuates outputs that control compressors, solenoid valves, or fans associated with each room's evaporator [8]. Through proportional-integral-derivative (PID) control or simpler on/off logic, the PLC maintains room temperatures within narrow tolerances, ensuring product quality [9].

Additionally, PLC systems can be networked with Supervisory Control and Data Acquisition (SCADA) platforms for centralized monitoring and control [10]. This integration provides facility managers with real-time visualization of system status, alarm management, and historical data logging for regulatory compliance and performance analysis [11]. It also facilitates predictive maintenance by alerting operators to anomalies before they result in equipment failure [12]. Energy efficiency is another significant benefit of using PLCs in cold storage temperature control. By optimizing compressor operation, reducing unnecessary defrost cycles, and coordinating cooling loads across different rooms, PLC-based systems can achieve substantial energy savings [13]. This is particularly important in today's industry, where energy costs are high and environmental regulations demand lower carbon footprints [14]. Moreover, the modular design of PLCs allows for easy system upgrades and maintenance. If additional rooms are added to the warehouse or if storage requirements change, the existing PLC system can be reprogrammed with minimal hardware modification [15]. This adaptability reduces downtime and enhances the warehouse's operational flexibility. In summary, PLCs provide a powerful solution for controlling temperatures in multi-evaporator cold storage warehouses. Their precision, flexibility, energy efficiency, and ease of integration with modern monitoring systems make them indispensable tools for preserving perishable goods. As the demand for high-quality, reliably stored food products continues to grow, the role of PLCs in cold storage automation will become increasingly vital.

Literature review

Research on the use of Programmable Logic Controllers (PLCs) in temperature control systems has expanded significantly over the past two decades. Bolton [1] provided a comprehensive

foundation for understanding PLC design and its application across various industrial environments, laying the groundwork for their adoption in cold storage solutions. Similarly, Petruzella [2] emphasized the adaptability of PLCs to different control tasks, including refrigeration system management, thus establishing the theoretical underpinnings of current cold storage automation strategies.

The integration of PLCs into supply chain management, especially in food storage logistics, has been explored by Hug [3], who noted that temperature management is a critical component of ensuring product quality from production to distribution. Tadokoro [4] further investigated the role of industrial automation in refrigeration, highlighting PLCs' capability to enhance precision and reduce human error in controlling cooling systems. Frank and Meyer [5] specifically addressed refrigeration system applications, discussing how PLCs optimize performance by adjusting compressor operation according to real-time temperature readings. Their findings suggested that properly programmed PLCs could lead to significant energy savings and improved storage stability for perishables. Randall [6] supported this view by outlining design principles for cold storage facilities that incorporate programmable systems for better environmental control. The functionality of sensors, particularly temperature sensors like PT100 and thermocouples, was detailed by Bent [7], who explained their crucial role in providing accurate data inputs to PLCs for effective feedback control. Johnson [8] expanded on this by discussing process control instrumentation, stating that the synergy between sensors and PLCs is pivotal for maintaining strict environmental parameters in multi-zone cold storage. In the realm of control strategies, Åström and Murray [9] described the advantages of feedback systems, including PID (Proportional-Integral-Derivative) controllers, which are often embedded within PLC programming to fine-tune temperature responses. Their research indicated that PID loops significantly improve system stability compared to simple on/off control, a necessity when dealing with sensitive products like meat and seafood. Boyer [10] and Buchanan [11] explored the enhancement of PLC systems with SCADA (Supervisory Control and Data Acquisition) technologies, emphasizing their contribution to centralized monitoring and remote management of industrial refrigeration units. Integration with SCADA was shown to enable better alarm handling, historical data analysis, and remote troubleshooting, thus increasing overall system resilience. Mobley [12] introduced the concept of predictive maintenance through automated monitoring systems, noting that real-time alerts generated by PLCs and SCADA can preemptively address equipment failures. This application is vital in cold storage where any downtime could result in massive financial and product losses. Energy management aspects were discussed by Murthy [13], who pointed out that PLC-driven control systems help optimize energy usage through precise compressor cycling and coordinated defrosting sequences. These practices align with broader environmental goals outlined by Razeghi and Wagner [14], who stressed the need for industries to adopt sustainable energy solutions. Turner [15] further validated the cost-effectiveness of implementing energy management strategies in refrigeration through automation, finding that facilities that deployed PLC systems saw notable reductions in operational expenses over time. In addition to these foundational studies, more recent research has focused on advanced PLC applications and smart cold storage design. Mohammed et al. [16] demonstrated how Internet of Things (IoT) integration with PLCs enhances data collection and allows for more dynamic control algorithms in cold storage environments. Their study indicated that IoT-enabled PLCs could adapt temperature set points based on predictive models rather than static schedules, improving energy efficiency and product preservation. Alvarez and

González [17] studied fault detection in refrigeration systems using PLCs combined with machine learning techniques. Their results showed that automated fault detection greatly reduces maintenance costs and prevents major failures, highlighting the evolving sophistication of PLC systems in critical industries. A report by the International Institute of Refrigeration [18] highlighted global trends toward automation in cold storage, identifying PLCs as a central technology in modern facilities. According to their findings, facilities that automated temperature control not only achieved better regulatory compliance but also experienced lower rates of spoilage and higher customer satisfaction. Santos and Pereira [19] explored the implementation of adaptive control strategies in multi evaporator systems, emphasizing the role of PLCs in managing the complexity of independently controlled storage rooms. They concluded that traditional single set point strategies are no longer sufficient for diverse product storage needs, and that PLCs offer the necessary flexibility. Finally, research by Chen and Yang [20] investigated hybrid control systems that combine PLCs with artificial intelligence for cold storage applications. They proposed systems capable of self-optimizing based on historical data trends, thereby further improving energy savings and operational robustness. Across all these studies, a common theme emerges: PLCs significantly enhance the efficiency, reliability, and adaptability of temperature control systems in cold storage warehouses. Their modular design, real-time processing capability, and ease of integration with modern technologies like SCADA and IoT position them as indispensable tools for the future of refrigerated storage. The evidence from the literature strongly supports the broader adoption of PLC-based control systems, particularly in industries where product quality and energy efficiency are paramount.

Case Study

This research focuses on the practical implementation of a Programmable Logic Controller (PLC)-based temperature control system in a real-world cold storage warehouse, consisting of a refrigeration unit equipped with three independent evaporators. Each evaporator serves a distinct storage room, dedicated respectively to meat, fish, and chicken products. The methodology adopted in this study encompasses system design, component selection, programming, installation, and testing phases, aiming to achieve precise and energy-efficient temperature management for each room.

System Overview

The refrigeration system consists of one central compressor unit coupled with three evaporators. Each evaporator cools a separate insulated chamber. The design allows each chamber to maintain specific temperature ranges based on the stored product type:

- **Meat Room:** -25°C to -30°C
- **Fish Room:** -4°C to -2°C
- **Chicken Room:** -10°C to -4°C

The compressor is operated based on collective demands from the three evaporators, while the solenoid valves are controlled independently to regulate refrigerant flow.

A schematic layout of the system is illustrated below:

[Compressor] → [Manifold] → [Solenoid Valves] → [Evaporator 1 (Meat Room)]
→ [Evaporator 2 (Fish Room)]

→ [Evaporator 3 (chicken Room)]

Sensors → [PLC] → [Control Outputs (Solenoids, Fans, Compressor)]
[HMI Panel] ↔ [PLC]

This arrangement ensures maximum flexibility, allowing each room to operate semi-independently within the integrated system.

Hardware Components

The chosen hardware components are detailed in Table 1:

Table 1: Shows components of hardware

Component	Specification	Function
PLC	Siemens S7-1200	Main control processor
Temperature Sensors	PT100 RTD sensors	Measure room temperatures
Solenoid Valves	24VDC coil, refrigeration-grade	Control refrigerant to evaporators
Compressor Starter	Contactors with overload protection	Start/stop compressor
Fans	AC axial fans	Circulate cold air in each room
HMI Panel	Siemens KTP400 Comfort Panel	Operator interface
Safety Devices	Pressure switches, E-stops	System protection

Each sensor is connected to the PLC analog input module, and control signals to valves, fans, and the compressor are handled via digital outputs.

Software Development

The control logic was developed using Siemens TIA Portal V16 software, using Ladder Logic (LD) as the primary programming language. The control program includes the following core elements:

1. Independent PID Control Loops

Each evaporator room has its own PID control loop tuned to maintain its target temperature. The PLC reads the temperature, compares it to the setpoint, and adjusts the solenoid valve operation accordingly.

- **Input:** Room temperature from PT100 sensor.
- **Output:** Opening/closing solenoid valve to allow refrigerant flow.
- **Tuning:** Manual Ziegler-Nichols method was used initially, then fine-tuned manually during field tests [9].

2. Compressor Management

The compressor is controlled based on a "cooling demand" signal generated by the PID loops:

- If any room requires cooling, the compressor starts.
- If no room demands cooling, the compressor stops after a short delay to prevent rapid cycling.

3. Defrost Management

Each evaporator is programmed with a separate defrost cycle, managed by timers within the PLC:

- Defrost is scheduled during low-demand periods.
- Only one evaporator is defrosted at a time to prevent overloading the system [5].

4. Alarms and Safety

The PLC monitors for abnormal conditions:

- High temperature alarms.
- Sensor failure detection (open circuit, short circuit).
- High pressure compressor shutdowns.

All alarms are displayed on the HMI with visual and audible indicators.

5. Data Logging

Temperature readings and alarm events are logged periodically into the PLC's internal memory and can be exported for analysis. This supports both troubleshooting and preventive maintenance efforts [12].

Installation and Commissioning

All equipment was installed according to the manufacturer's specifications and IEC 60204-1 standards for industrial machinery wiring. Wiring checks and insulation resistance tests were performed before powering up. A staged commissioning approach was used:

- **Dry run testing** of control logic without refrigerant.
- **Live system testing** under no-load, partial load, and full-load conditions.

Field adjustments were made to optimize PID parameters, compressor run-times, and defrost intervals based on real-world performance.

Testing and Validation

Testing focused on verifying system stability, accuracy, and responsiveness:

- **Temperature Stability:** Each room maintained its setpoint within $\pm 0.5^\circ\text{C}$ tolerance under steady-state conditions.
- **Response Testing:** System reaction to sudden heat loads (e.g., door opening) was measured. Recovery time was consistently under 10 minutes for all rooms.
- **Energy Consumption:** Using a power analyzer, total energy use was reduced by approximately 18% compared to the baseline system previously using mechanical thermostats [14].
- **System Uptime:** Over three months of continuous operation, the system recorded 99.5% uptime with only minor maintenance interventions.

Challenges and Solutions

Several challenges and corresponding solutions included:

- **Sensor Calibration Drift:** Implemented monthly manual recalibration schedule based on a reference thermometer.
- **Software Bugs During Defrost:** Early versions caused unnecessary compressor stops; corrected by isolating defrost cycles from the cooling demand logic.

- **Operator Training Needs:** Developed simple HMI screens with multi-language support to ease the learning curve for local staff.

Safety and Redundancy

To ensure maximum reliability, redundant safety layers were added:

- Hardwired interlocks for pressure safety independent of PLC control.
- Watchdog timers within the PLC to detect program freezes.
- Manual override switches to operate solenoids and compressor manually during emergencies.

Results and Discussion

The implementation of the PLC-based multi-evaporator temperature control system yielded significant improvements in operational efficiency, temperature stability, and energy consumption. The individual PID loops maintained the target temperatures in each room within a narrow tolerance of $\pm 0.5^{\circ}\text{C}$, even during dynamic events such as door openings or product loading. These results highlight the accuracy and responsiveness of the control logic under varying thermal loads. Energy consumption analysis demonstrated an approximate **18% reduction** compared to the previous thermostat-based system. This efficiency gain is attributed to optimized compressor control, minimized defrost overlap, and precise refrigerant flow regulation through solenoid valves. The integration of separate defrost scheduling further prevented unnecessary compressor shutdowns, enhancing the overall system continuity. System uptime was recorded at **99.5% over a three-month period**, indicating strong reliability. Minor downtime events were mostly attributed to initial software tuning and sensor recalibration. The inclusion of watchdog timers, hardware interlocks, and manual overrides contributed to safety redundancy and fault tolerance. Notably, the system's responsiveness was validated during stress testing. Each chamber recovered to its set point temperature in under **10 minutes** after sudden heat introduction, such as prolonged door opening. This rapid recovery is critical in preserving the quality of sensitive food products. User interaction was also improved via an intuitive HMI interface with multi-language support, reducing operator training time and minimizing human error. This aligns with modern trends in cold storage automation where user-friendliness is crucial for widespread adoption.

Conclusion

This study successfully demonstrated the practical application and advantages of a PLC-based control system in managing multi-evaporator refrigeration systems within cold storage environments. The system achieved high-precision temperature regulation across three independently controlled storage rooms—meat, fish, and poultry—each with distinct thermal requirements. By leveraging PID control algorithms, real-time sensor feedback, and programmable logic, the system maintained stable temperatures within a narrow tolerance, reduced energy consumption, and improved overall operational reliability. These outcomes validate the superiority of PLC technology over conventional thermostat-based and electromechanical control methods, especially in applications where accuracy, energy efficiency, and adaptability are critical. Moreover, the project highlighted the importance of well-integrated hardware and software in achieving a robust and scalable control infrastructure. The Siemens S7-1200 PLC, combined with PT100 sensors and SCADA-compatible interfaces, provided a modular platform that can be easily

extended or modified to suit future facility needs. The HMI interface enhanced usability for operators, ensuring that even non-technical staff could monitor and control the system with ease. This user-centric design is essential for widespread adoption and successful operation in real-world industrial settings. From an operational standpoint, the system's performance during stress testing and its 99.5% uptime over an extended monitoring period underscored its reliability and fault tolerance. The inclusion of alarm management, safety interlocks, and manual override options contributed to its robustness and ensured continuity of operation under abnormal conditions. Furthermore, the 18% reduction in energy use compared to legacy systems demonstrates the economic and environmental benefits of adopting programmable automation in cold storage facilities.

Recommendations for future improvements include:

1. **IoT Integration** – Enable remote access and data analytics through cloud platforms for predictive insights and remote diagnostics.
2. **Machine Learning Algorithms** – Incorporate adaptive control based on product load profiles or historical temperature trends for even greater efficiency.
3. **Extended Data Logging** – Integrate long-term storage and graphical analysis tools to support audits, compliance, and maintenance planning.
4. **Automated Calibration** – Introduce auto-calibration routines for temperature sensors to reduce manual intervention and enhance accuracy.
5. **Redundant PLC System** – For critical storage applications, consider using hot standby PLCs to ensure uninterrupted control in case of hardware failure. By implementing these enhancements, future cold storage systems can further reduce energy costs, improve food safety assurance, and adapt to evolving industrial automation standards.

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