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Posted Date: 7 April 2026

doi: 10.20944/preprints202604.0500.v1

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A DDC-Based Integrated Electrical and Instrumentation Control System Architecture for Unconventional Oil Production Plants

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Abstract

Unconventional oil production plants are complex industrial systems characterized by harsh operating conditions, modular facility configurations, and tightly coupled electrical, instrumentation, and control subsystems. Conventional centralized control architectures, such as Distributed Control Systems (DCS) and Programmable Logic Controller (PLC)-based systems, often exhibit structural limitations in scalability, maintainability, and subsystem integration when applied to such distributed plant environments. This study proposes a Direct Digital Control (DDC)-based integrated electrical and instrumentation control system architecture for unconventional oil production plants from a systems engineering perspective. The proposed architecture adopts distributed field-level DDC controllers as autonomous system nodes, enabling direct processing of instrumentation signals and coordinated integration with electrical subsystems through a network-based structure. This transforms the control platform into a system-of-systems architecture in which process, electrical, instrumentation, safety, and supervisory layers operate as interoperable subsystems. The proposed system was implemented in a pilot-scale unconventional oil production plant to evaluate its practical applicability. The results indicate that the proposed architecture improves system scalability, modular adaptability, maintenance efficiency, and operational robustness compared with conventional centralized architectures. In particular, system expansion and module integration were achieved without structural redesign of the overall control platform. This study provides a practical architectural framework for integrated control of complex industrial plants and offers a foundation for future extensions toward smart plant operation, digital twin integration, and intelligent industrial system-of-systems engineering.

Keywords: unconventional oil production plant; direct digital control; integrated control system; system architecture; system-of-systems; industrial automation; electrical and instrumentation integration; modular plant

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1. Introduction

Unconventional oil production plants, including oil sands and heavy oil facilities, represent complex industrial systems characterized by harsh operating conditions, modular plant layouts, and tightly coupled electrical, instrumentation, and control subsystems. These plants must be regarded as complex industrial systems rather than simple process units [1–4]. However, conventional centralized control architectures struggle to support such system configurations. Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC) have been widely used in oil and gas facilities. Although these technologies provide proven reliability, they exhibit limitations in scalability, system integration, and lifecycle maintainability when applied to modular unconventional oil plants. In particular, the separation between electrical and instrumentation subsystems often leads to fragmented system management and reduced operational efficiency. Direct Digital Control (DDC) systems, originally developed for building automation, provide a distributed

doi:10.20944/preprints202604.0500.v1

control paradigm in which field-level controllers operate as autonomous system nodes. Their network-based structure enables scalable and modular system integration. However, the application of DDC-based architectures in large-scale industrial production plants remains insufficiently explored in academic literature. This study proposes a DDC-based integrated electrical and instrumentation control system architecture for unconventional oil production plants from a systems engineering perspective. The objective is not merely to introduce a new control method, but to establish a system architecture framework that integrates heterogeneous subsystems into a coherent system-of-systems structure.

The main contributions of this study are:

1. Proposal of a system-oriented DDC-based integrated control architecture.
2. System-level implementation and industrial validation in a pilot plant.
3. System performance evaluation from scalability and maintainability perspectives.
4. Establishment of a system-of-systems framework for future smart plant evolution.

2. System Requirements of Unconventional Oil Production Plants

Unconventional oil production plants, such as SAGD, ES-SAGD, and CSS facilities, operate as complex industrial systems characterized by harsh thermodynamic environments, multiphase flow behavior, and tightly coupled subsystems. Unlike conventional oil production plants, these facilities must be treated as integrated system-of-systems structures in which process, electrical, instrumentation, safety, and operational subsystems interact dynamically to determine overall plant performance. Therefore, control system design must be derived from system-level requirements rather than isolated component-level considerations.

This shift provides a practical foundation for future smart plant evolution. Unconventional Oil Production Plant as a System-of-System.

2.1. Environmental and Process System Requirements

Thermal recovery processes require continuous handling of high-temperature and high-pressure fluids, often exceeding 200 °C, together with large variations in phase composition and flow rates. These operating conditions introduce strong nonlinearities and uncertainties in process dynamics, which demand robust and adaptive system behavior. From a systems engineering perspective, unconventional oil production plants must be treated as systems-of-systems composed of multiple autonomous yet interoperable subsystems [5–9]. These subsystems include thermal processing units, electrical power systems, instrumentation and control systems, and safety systems, each of which must operate autonomously while maintaining system-wide coordination.

- Thermal robustness of system components
- Dynamic stability under transient conditions
- Fault-tolerant sensing and actuation
- Resilience to signal degradation and noise

2.2. Structural System Requirements for Modular Plants

Recent studies report that unconventional oil production plants increasingly adopt modular construction and phased expansion strategies to reduce project risk and improve execution efficiency. However, modularization introduces system evolution as a fundamental requirement.

Accordingly, the control system must support:

- Plug-and-play module integration
- Preservation of system integrity during topology changes
- Minimal re-engineering during system expansion
- Consistent system behavior under subsystem additions

These requirements indicate that the plant control system must be designed as an evolutionary system architecture

2.3. Electrical Subsystem Integration Requirements

Electrical subsystems play a critical role in ensuring safe and reliable operation, particularly through fault detection and protection mechanisms that directly affect process availability [20,21]. Modern oil production plants require real-time monitoring of motor health, protection relay coordination, and predictive fault detection. Electrical data must therefore be treated as core system information rather than auxiliary monitoring signals.

System-level electrical integration enables:

- Coordinated electrical-process fault diagnosis
- Improved power reliability and energy efficiency
- Reduction of unplanned downtime

2.4. Instrumentation Subsystem Requirements

Instrumentation systems provide essential process visibility and control feedback, enabling stable operation and early detection of abnormal conditions [14]. In unconventional oil environments, sensors are exposed to fouling, vibration, corrosion, and thermal stress, which significantly affect measurement reliability.

Therefore, instrumentation systems must support:

- Redundant measurement structures
- Voting logic for safety-critical variables
- Self-diagnostic and validation functions
- System-level data consistency management

2.5. Safety as a System Property

Safety in unconventional oil production plants cannot be implemented as an isolated subsystem. Instead, safety emerges from coordinated interactions among process control, electrical protection, safety instrumented systems, and human operators. International functional safety standards emphasize that safety must be considered as a system property achieved through architectural design rather than individual component certification. Accordingly, the control architecture must preserve logical independence while enabling controlled inter-system communication.

doi:10.20944/preprints202604.0500.v1

2.6. Operational and Maintenance System Requirements

Operational sustainability requires remote monitoring, rapid fault localization, and knowledge preservation through data historization. From a systems engineering perspective, the control system must therefore function as both an operational platform and an organizational knowledge system.

2.7. Summary of System-Level Requirements

Based on the above analysis, unconventional oil production plants must be regarded as system-of-systems structures in which overall system behavior emerges from subsystem coordination. Consequently, the plant control system must satisfy the following system-level requirements:

1. Distributed system architecture
2. Modular adaptability
3. Integrated subsystem management
4. Evolutionary scalability
5. Emergent safety and reliability

These requirements cannot be fully satisfied by conventional centralized control architectures, thereby motivating the DDC-based system architecture proposed in this study.

3. Limitations of Conventional Control System Architectures

Conventional control system architectures in oil and gas production plants have been predominantly based on centralized Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC). Although these architectures have demonstrated reliability in conventional process environments, they exhibit fundamental limitations when applied to modular and distributed unconventional oil production plants [1–4]. Figure 2 illustrates these structural limitations by comparing centralized DCS and fragmented PLC-based control architectures from a system integration perspective.

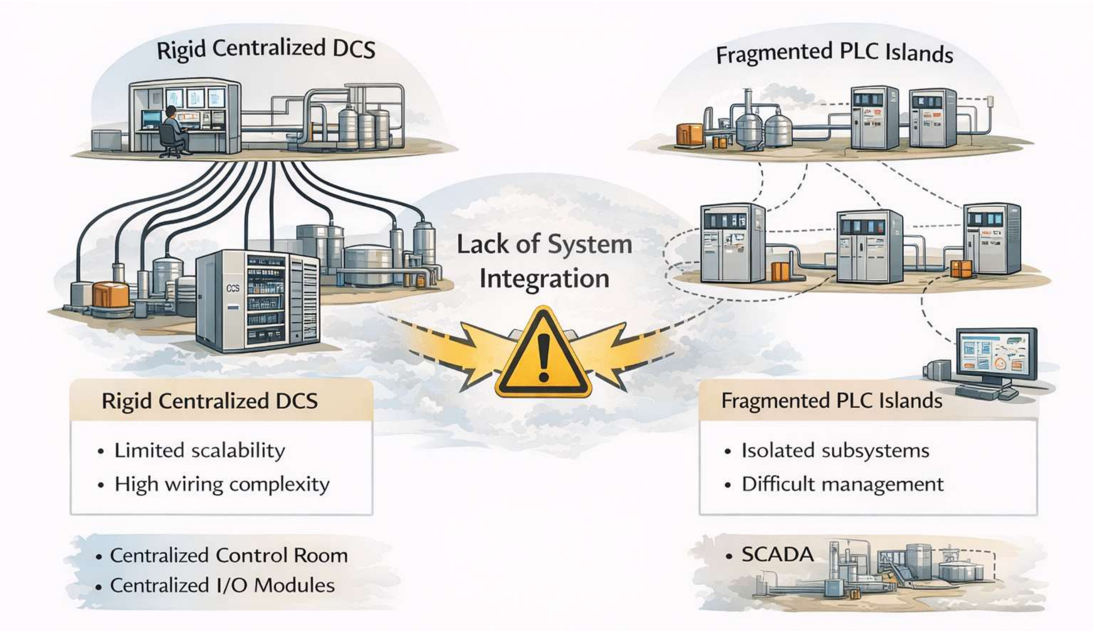

Figure 2. Structural limitations of conventional centralized DCS and fragmented PLC-based control architectures.

From a systems engineering perspective, these limitations originate from structural mismatches between centralized control philosophies and the evolving system requirements of modern industrial plants.

3.1. Centralized DCS Architectures

Conventional centralized DCS architectures suffer from scalability limitations and rigid system configurations that hinder modular expansion [10–14]. This structural characteristic introduces several system-level constraints:

- Scalability limitation: Modular expansion requires significant re-engineering of I/O allocation and control logic.
- Wiring complexity: Long-distance signal cabling increases installation cost and signal integrity risks.
- System rigidity: Centralized logic structures restrict flexible reconfiguration of control topology.
- Maintenance impact: Fault isolation often propagates across multiple subsystems, increasing downtime.

From a system perspective, these characteristics reduce the plant's ability to evolve as an adaptive system.

3.2. Limitations of PLC-Based Architectures

PLC-based control architectures introduce fragmentation across subsystems, leading to increased integration complexity and limited system-wide visibility [10–13]. However, when applied at plant scale, they introduce different system integration challenges:

- Fragmented system integration: Multiple PLC islands require complex middleware and communication mapping.
- Heterogeneous control environments: Vendor-specific implementations complicate system harmonization.
- Limited system transparency: Unified system monitoring and historization become difficult to maintain.
- Scalability degradation: Communication load increases disproportionately with system expansion.

As a result, PLC-based plant-scale systems often evolve into loosely coupled subsystems rather than a coherent system.

3.3. Electrical and Instrumentation Subsystem Separation

In conventional architectures, electrical and instrumentation subsystems are typically managed by separate platforms or engineering domains. This separation leads to:

- Inconsistent system data models
- Delayed fault diagnosis across subsystem boundaries
- Redundant maintenance workflows
- Reduced system-level situational awareness

From a systems viewpoint, this separation prevents holistic system optimization and limits cross-domain intelligence.

3.4. System-Level Consequences of Subsystem Separation

The separation of electrical and instrumentation subsystems results in reduced fault correlation capability and delayed system-level decision-making [15,19]. Due to the above limitations, conventional control architectures exhibit the following system-level deficiencies:

1. Reduced system adaptability
2. Increased lifecycle engineering cost
3. Limited support for modular plant evolution
4. Degraded fault management efficiency
5. Inhibited system-of-systems integration

doi:10.20944/preprints202604.0500.v1

These deficiencies prevent conventional architectures from supporting unconventional oil production plants as integrated system-of-systems.

3.5. Summary of Architectural Limitations

Table 1. Summary of limitations of conventional control architectures from a system perspective.

Aspect	DCS-Based Architecture	PLC-Based Architecture
Scalability	Limited by centralized I/O structure	Limited by communication fragmentation
Subsystem Integration	Electrical and instrumentation separation	Heterogeneous PLC integration complexity
Wiring Complexity	Extensive centralized cabling	Distributed but unstructured wiring
Fault Diagnosis	Centralized diagnosis delays isolation	Decentralized diagnosis lacks system view
System Evolution	Poor adaptability to modular expansion	High engineering effort for expansion

3.6. System Architecture Implication

The analysis demonstrates that conventional DCS- and PLC-based architectures are fundamentally misaligned with the system requirements of modular unconventional oil production plants. These architectures were not originally designed to support system evolution, subsystem interoperability, and system-of-systems integration. Therefore, a new control system architecture must be designed from a system architecture perspective, rather than as a simple extension of existing control paradigms. This necessity motivates the DDC-based integrated system architecture proposed in this study.

4. Proposed DDC-Based Integrated System Architecture

The proposed DDC-based architecture integrates electrical and instrumentation subsystems at the field level, enabling distributed autonomy and system-wide coordination [5,6,15–19]. To overcome the structural limitations of conventional DCS- and PLC-based control architectures discussed in Section 3, this study proposes a DDC-based integrated electrical and instrumentation control system architecture from a systems engineering perspective. he proposed architecture is designed to support modular plant evolution, subsystem interoperability, and system-of-systems integration, which are essential requirements for unconventional oil production plants.

4.1. Architectural Design Philosophy

The proposed architecture is based on the following system design principles:

1. Distributed autonomy: Each field controller operates as an autonomous system node.
2. System interoperability: Electrical and instrumentation subsystems share a unified data and communication structure.
3. Evolutionary scalability: System expansion is achieved without structural redesign.
4. System resilience: Fault tolerance and redundancy are embedded at the architectural level.

Unlike conventional centralized architectures, the proposed system treats each control node as an independent yet cooperative subsystem.

doi:10.20944/preprints202604.0500.v1

4.2 Overall System Architecture

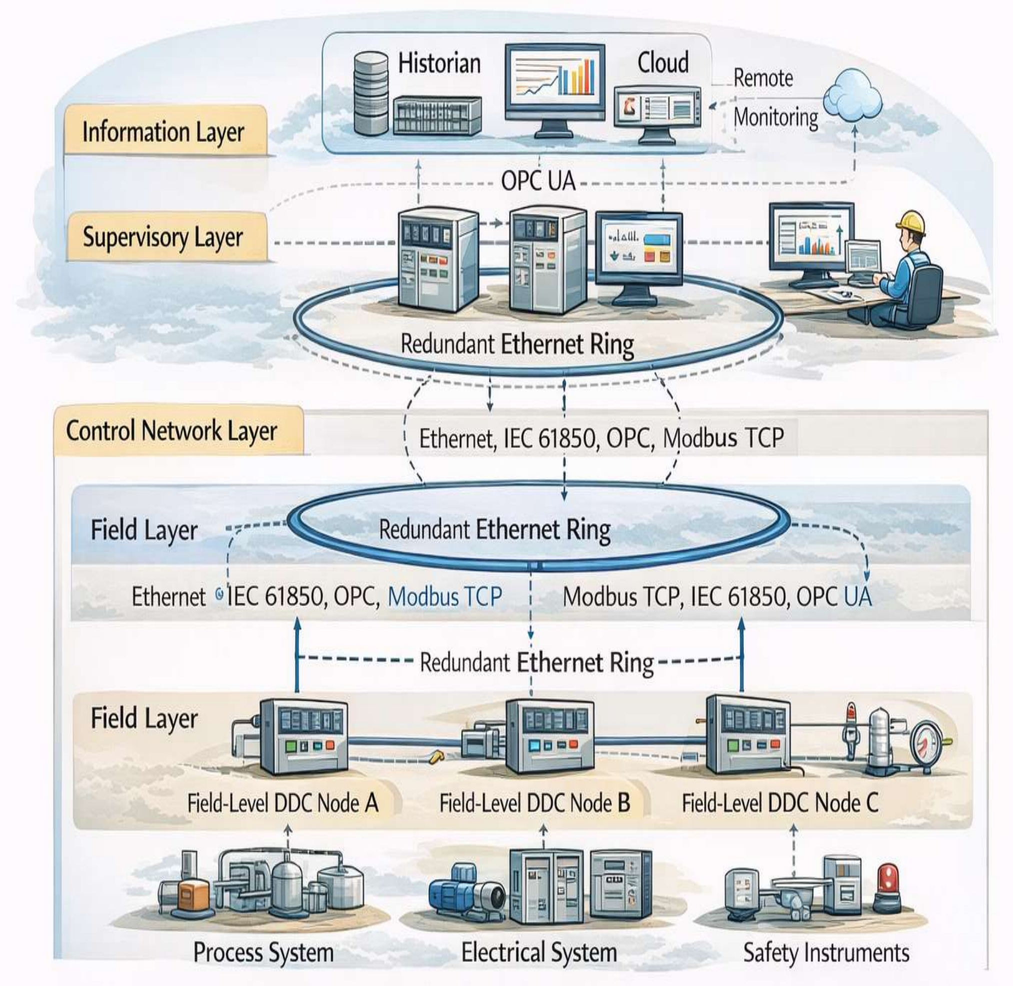

Figure 3. Proposed DDC-based integrated electrical and instrumentation control system architecture illustrating distributed field-level autonomy, subsystem interoperability, and system-of-systems integration.

The proposed architecture consists of four system layers, as shown in Figure 3:

1. Field DDC Layer
2. Control Network Layer
3. Supervisory Layer
4. Information Layer

Each layer operates independently while maintaining system-level interoperability.

4.3 Field-Level DDC Node Structure

Each DDC node performs:

- Instrument signal acquisition
- Control logic execution
- Electrical equipment monitoring
- Local safety interlock processing
- Network communication

This transforms the DDC controller into a cyber-physical system node rather than a simple I/O device.

doi:10.20944/preprints202604.0500.v1

4.4 Electrical and Instrumentation Integration Mechanism

In the proposed architecture, electrical and instrumentation subsystems are integrated through standardized communication protocols such as Modbus TCP, IEC 61850, and OPC UA.

This integration enables:

- Unified fault diagnosis
- Coordinated control actions
- Cross-domain data consistency
- System-level situational awareness

4.5 System-of-Systems Perspective

From a system-of-systems viewpoint, the proposed architecture consists of:

- Process control subsystem
- Electrical management subsystem
- Instrumentation sensing subsystem
- Safety supervision subsystem
- Operation and maintenance subsystem

Each subsystem operates autonomously while contributing to overall system behavior.

4.6 Architectural Comparison

Table 2. Comparison of control system architectures from a system perspective.

Aspect	Conventional DCS	Conventional PLC	Proposed DDC Archi-tecture
System topology	Centralized	Fragmented	Distributed integrated
Subsystem Integration	Limited	Partial	Unified
Scalability	Low	Medium	High
Modular adaptability	Poor	Medium	Excellent
System-of-systems support	No	Partial	Full

4.7 Architectural Advantages

The proposed architecture provides the following system-level advantages:

1. Reduced wiring complexity
2. Improved system scalability
3. Enhanced subsystem interoperability
4. Improved fault isolation capability
5. Support for modular plant evolution

These advantages directly address the limitations identified in Section 3.

4.8 Architectural Implication

From a systems engineering perspective, the proposed architecture shifts the control system role from a centralized automation platform to a distributed system integrator. This paradigm shift enables unconventional oil production plants to evolve as adaptive, resilient, and intelligent industrial systems

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5. Electrical and Instrumentation Integration Methodology

The proposed DDC-based system architecture integrates electrical and instrumentation subsystems within a unified system framework to achieve system-level interoperability and operational consistency.

5.1 Integration Philosophy

Conventional plants manage electrical and instrumentation subsystems independently, which limits system-level fault diagnosis and coordinated control. In contrast, the proposed methodology treats both subsystems as cooperative elements of a single cyber-physical system. The integration methodology is based on three principles:

1. Unified communication structure
2. Common data modeling
3. Cross-domain event correlation

5.2. Communication Integration

Electrical equipment (MCCs, VFDs, protection relays) and instrumentation devices communicate with DDC nodes using standardized protocols:

- IEC 61850 for electrical protection and monitoring
- Modbus TCP/IP for field devices
- OPC UA for supervisory and information layers

Standardized communication protocols enable interoperability between heterogeneous devices while maintaining system independence [16–18].

5.3 Data Model Harmonization

All process, electrical, and safety variables are mapped into a unified system data model, enabling:

- Consistent naming conventions
- Unified alarm classification
- Cross-domain data correlation

This harmonization eliminates subsystem data silos.

5.4 Coordinated Control and Diagnosis

The integrated structure allows:

- Electrical fault impact on process variables to be automatically correlated
- Process disturbances to be traced back to electrical root causes
- Maintenance recommendations to be generated based on system-wide behavior

Table 3. Comparison of subsystem integration approaches.

Aspect	Conventional Approach	Proposed Method
Data structure	Separated	Unified
Fault diagnosis	Subsystem-level	System-level
Alarm management	Independent	Correlated
Maintenance support	Reactive	Predictive

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6. Safety and Reliability Framework

6.1 Safety as a System Property

In the proposed architecture, safety is treated as an emergent system property rather than an isolated function. In the proposed architecture, safety is treated as an emergent system property arising from coordinated subsystem interactions rather than isolated safety functions [20–22]. Safety performance results from coordinated interactions among:

- Basic process control system
- Electrical protection system
- Safety instrumented system
- Fire and gas system
- Human–machine interface

6.2 Functional Independence and System Coordination

Logical independence between safety and control systems is preserved in compliance with IEC 61511 and IEC 61508. However, controlled data exchange enables:

- Context-aware operator response
- System-wide emergency coordination
- Improved post-event analysis

6.3. Reliability and Redundancy Strategy

Reliability is ensured through multi-layer redundancy:

- Network redundancy (dual Ethernet rings)
- Controller redundancy
- Power supply redundancy

Reliability is enhanced through redundancy and predictive maintenance strategies applied across the integrated system architecture [23,24].

Table 4. Reliability design features of the proposed architecture.

Layer	Redundancy Strategy
Network	Dual ring Ethernet
Controller	Hot standby
Power	Dual power supply
Data	Historian mirroring

6.4 System Resilience

The proposed framework enables graceful degradation, in which local subsystems maintain autonomous operation even under partial system failures.

7. Pilot Plant Validation

7.1 Pilot Plant Description

The proposed system architecture was implemented in a 600 BPD unconventional oil production pilot plant. The facility includes:

- FWKO, heater treater, separators

- Steam generation and injection systems
- Produced water treatment units

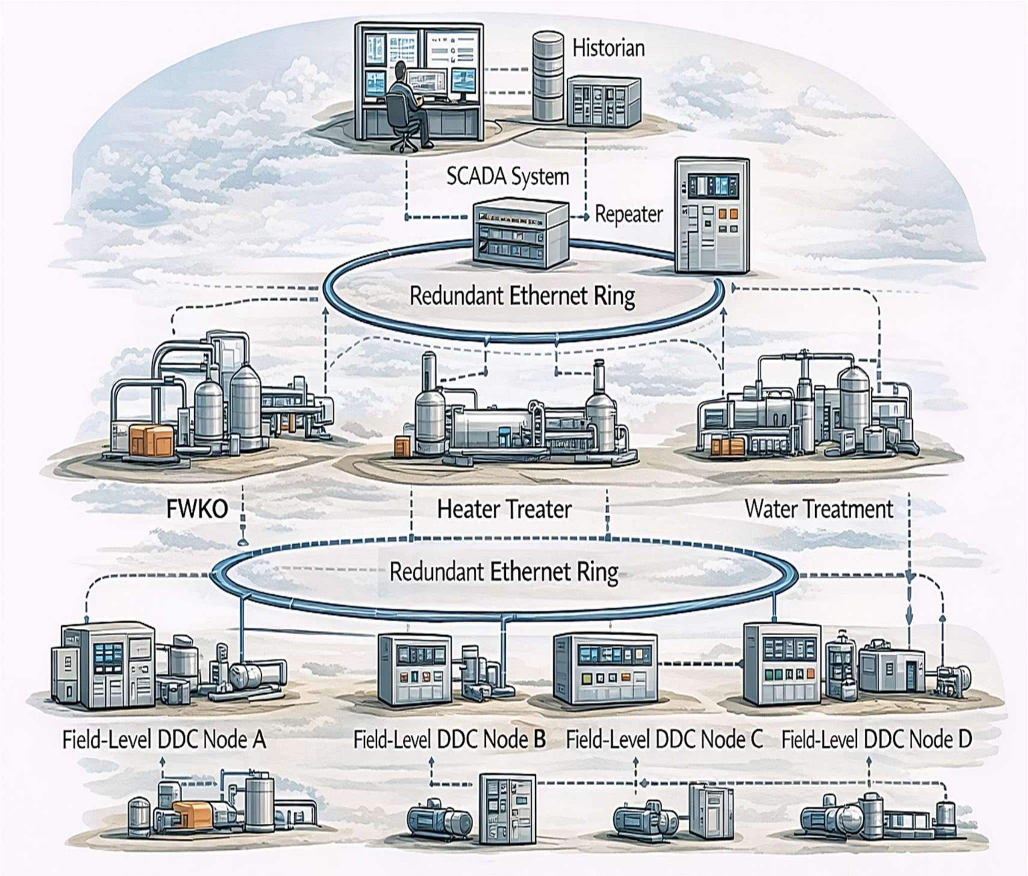

Figure 4. Deployment of the proposed DDC-based integrated control system in a 600 BPD pilot-scale unconventional oil production plant.

7.2 System Configuration

- DDC nodes: 24
- Total I/O points: 1,150
- Control loops: 280
- Network: Redundant Ethernet ring

7.3 Performance Evaluation Metrics

The system was evaluated based on:

- Wiring reduction
- System expansion effort
- Maintenance response time
- System availability

The baseline was established based on a centralized DCS-oriented architecture with equivalent functional requirements, including the same process units, I/O scale, and supervisory functions. The comparative indicators presented in Table 5 were derived from engineering design data, commissioning records, and operational maintenance observations collected during pilot plant implementation. To ensure a meaningful comparison, the performance metrics presented in this study were evaluated relative to a conventional centralized control system configuration defined as the baseline engineering reference for the same pilot plant capacity and subsystem composition. The baseline was established based on a centralized DCS-oriented architecture with equivalent functional requirements, including the same process units, I/O scale, and supervisory functions. The comparative indicators presented in Table 5 were derived from engineering design data, commissioning records, and operational maintenance observations collected during pilot plant implementation.

Table 5. Performance comparison between the conventional DCS architecture and the proposed DDC-based architecture.

Metric	Conventional DCS	Proposed DDC
Wiring length	100%	62%
Expansion time	100%	55%
Maintenance downtime	100%	68%
System availability	98.2%	99.4%

7.4 Validation Results

The pilot plant results confirm that:

- The proposed architecture supports modular expansion without system restructuring.
- Integrated fault diagnosis reduces troubleshooting time.
- System availability improves due to distributed autonomy

7.5. Discussion of Practical Implications

From a systems engineering perspective, the pilot plant demonstrates that distributed DDC architectures can effectively function as system integrators in complex industrial environments. The pilot plant validation confirms that the proposed architecture is suitable for modular industrial deployment and scalable system evolution. [25–27]

8. Conclusions and Future Work

This study proposed a DDC-based integrated electrical and instrumentation control system architecture for unconventional oil production plants from a systems engineering perspective. Unlike conventional DCS- and PLC-based architectures, the proposed system adopts distributed field-level autonomy, unified subsystem integration, and a system-of-systems framework.

The architecture was implemented and validated in a 600 BPD pilot-scale unconventional oil production plant. The validation results demonstrated improved scalability, modular adaptability, maintenance efficiency, and system availability. In particular, the proposed architecture enabled system expansion and module integration without structural reconfiguration of the control system.

From a systems viewpoint, the proposed architecture transforms the role of control systems from centralized automation platforms into distributed system integrators This shift provides a practical foundation for future smart plant evolution.

Future research will focus on cybersecurity integration, digital twin coupling, AI-based predictive operation, and standardized system modeling frameworks to further enhance system intelligence and resilience.

doi:10.20944/preprints202604.0500.v1

Author Contributions: Conceptualization, J.-H.J.; methodology, J.-H.J.; system architecture design, J.-H.J.; software, J.-H.M.; validation, J.-H.M.; formal analysis, J.-H.J. and J.-H.M.; investigation, J.-H.J.; writing—original draft preparation, J.-H.M.; writing—review and editing, J.-H.J.; supervision, J.-H.J.; project administration, J.-H.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Korea Agency for Infrastructure Technology Advancement (KAIA), funded by the Ministry of Land, Infrastructure and Transport, Republic of Korea (Grant No. RS-2022-00143644).

Data Availability Statement: The data presented in this study are not publicly available due to confidentiality restrictions related to industrial pilot plant operation and project agreements.

Conflicts of Interest: The authors declare no conflict of interest.

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