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Architectural Patterns for Distributed Energy Management Systems Based on Programmable Logic Controllers

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Abstract— *The article is dedicated to the explanation of architectural patterns that shape distributed energy management systems implemented through programmable logic controllers. Relevance is determined by the rapid spread of distributed renewable generation, storage units, and supervisory platforms across distributed energy sites, where stable operation increasingly depends on how heterogeneous components are coordinated rather than on the performance of any single device. Novelty lies in the interpretation of PLC-based energy management as a layered control environment in which signal validation, semantic normalization, communication mediation, mode logic, and predictive adjustment are structurally interconnected. The work describes the internal organization of these architectures and studies how control functions are redistributed between field devices, PLC loops, gateways, supervisory systems, and analytical layers. Special attention is given to interoperability under protocol fragmentation, export-limiting behavior, and the separation of control-critical data from telemetry streams. The work sets itself the goal of explaining how such architectures preserve stability under variability and partial degradation. Analytical review, comparative interpretation, conceptual grouping, and synthesis are used to solve this task. The conclusion describes the structural conditions of resilient design. The article will be useful for automation engineers, system integrators, and researchers working with hybrid distributed energy infrastructures.*

Keywords— ***distributed energy management systems, hybrid energy systems, utility-scale PV, programmable logic controllers, SCADA architecture, predictive control, interoperability, signal normalization***

I. INTRODUCTION

Distributed energy infrastructures, particularly in large-scale photovoltaic and hybrid energy sites, have shifted their operational logic. Photovoltaic generation, battery storage, intelligent metering, and supervisory software no longer operate as separate technical additions attached to previously centralized automation structures. They alter the core itself. Once these elements begin to exchange signals, react to grid limits, and modify one another's operating states, architectural design stops being a secondary engineering concern and becomes the mechanism through which operational stability is either preserved or lost.

This problem has practical weight because modern installations rarely consist of homogeneous equipment families with fully transparent specifications. In actual deployments, controllers receive signals from devices that differ in protocol behavior, address structure, timing discipline, scaling conventions, and update semantics. Under such conditions, reliable energy management depends less on nominal compatibility and more on the way the

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control architecture interprets, filters, redistributes, and prioritizes information flows. Instability often begins there. Not in power electronics alone.

The purpose of the study is to explain the architectural mechanisms through which PLC-based distributed energy management systems maintain stable, scalable, and interpretable control under conditions of heterogeneity, latency, and fluctuating energy exchange. This purpose is unfolded through three research objectives.

1) to analyze how control responsibilities are redistributed across field, PLC, supervisory, and predictive layers in architectures that combine real-time execution with slower analytical coordination.

2) to identify the mechanisms by which heterogeneous device signals are normalized, validated, and transformed into unified control variables suitable for scalable deployment.

3) to evaluate how mode-based logic, communication constraints, and predictive extensions reshape operational behavior in hybrid distributed energy environments.

The hypothesis of the study is formulated as follows: architectural stability in PLC-based distributed energy management systems is achieved not through uniformity of equipment, but through layered separation of signal interpretation, deterministic execution, and supervisory adaptation; when these layers are coherently organized, the system preserves controllability even under protocol inconsistency, communication delay, and partial degradation.

The novelty of the study follows from a visible insufficiency in existing research. Many publications describe communication frameworks, predictive controllers, SCADA environments, or platform solutions in relative isolation. Fewer works explain how these elements function together as one architectural mechanism. The present article addresses that gap by reconstructing the internal structure of PLC-based energy management systems through the interaction of operational layers, signal pathways, control modes, and validation procedures. The intended contribution is not another catalog of technologies. It is an explanatory model of how the system actually holds together.

II. METHODS AND MATERIALS

The research design combines analytical review with conceptual architectural modeling. Such a design was selected because the problem under consideration is not limited to performance comparison between devices or algorithms. The central task lies elsewhere: to reconstruct how heterogeneous implementations reveal recurring structural mechanisms. For that reason, the procedure moved from source retrieval to staged filtering, then to grouped interpretation, and only after that to synthesis of architectural patterns.

The empirical basis of the analysis was formed from publications indexed in international scientific databases and distributed through open-access engineering journals. The search space included Scopus-indexed and Web of Science–indexed materials, along with major journal platforms specializing in energy systems, industrial automation, and energy infrastructure engineering. Open-access access conditions mattered here for a practical reason: the study required complete architectural descriptions, not abstract-level summaries.

The search strategy relied on combined keyword clusters linked through logical operators. The core search strings included “hybrid energy system control” AND “programmable logic controller,” “PLC” AND “SCADA architecture” AND “hybrid power system” AND “flow-based SCADA” AND “control,” “predictive control” AND “distributed energy management” AND “utility-scale PV control architecture” AND “PLC” “semantic rule-based” AND “energy management,” and “OPC UA” OR “MQTT” AND “industrial gateway” AND “energy.” These combinations were expanded and narrowed iteratively in order to capture both infrastructure-focused and architecture-focused studies. That was necessary because relevant publications do not always describe themselves under one shared vocabulary.

The time range of the search covered 2021–2026. This interval was chosen deliberately. Earlier studies often describe foundational automation ideas, yet they do not reflect the current interaction between photovoltaic resources, storage coordination, lightweight middleware, semantic

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control, and predictive energy system analytics. The search in its initial stage identified 34 publications. After duplicate removal, 29 records remained. Title and abstract filtering excluded studies centered exclusively on component-level hardware testing, thermal comfort assessment without control architecture, purely economic optimization, or generic smart-home discussions lacking programmable control logic. Thirteen studies passed to full-text assessment. Three additional publications were excluded at that stage because they did not provide sufficient architectural detail or did not link control design to operational mechanisms. The final analytical sample consisted of 10 sources.

Inclusion criteria were defined in a way that preserved architectural relevance. A study was retained if it described at least one of the following with sufficient analytical depth: PLC-centered control design, SCADA or supervisory coordination in hybrid energy systems, protocol mediation and interoperability, predictive or rule-based extensions integrated into control architecture, or system-layer decomposition linking field devices to supervisory logic. Exclusion criteria removed publications focused only on isolated algorithms, user-facing interfaces without control infrastructure, device manufacturing characteristics, or simulation exercises detached from operational implementation.

The selected studies were not interpreted one by one in a sequential literature parade. Instead, they were grouped according to the mechanisms they revealed. One group concentrated on real-time and hierarchical control architectures, showing how deterministic execution remains local even when analytical intelligence is externalized. These studies clarified the coexistence of fast PLC loops and slower supervisory or cloud-linked processes. Another group dealt with interoperability, gateways, and data semantics. Here the dominant mechanism was not simple protocol translation but signal reinterpretation through mapping, normalization, and abstraction. A third group described open-source supervisory and SCADA environments, where modularity, MQTT-based exchange, and flow-based orchestration frameworks revealed how lightweight infrastructures can support distributed monitoring and command propagation. A fourth analytical cluster addressed predictive and semantic extensions, where operating modes, fuzzy logic, learned transitions, and declarative rule structures reshaped control from reactive response toward anticipatory coordination.

Across these grouped directions, several recurring relationships became visible. Measurement infrastructures capture raw states, yet those states do not enter control logic unchanged. They are processed through validation layers. Communication networks transmit data, yet transmission speed alone does not define control quality; timing suitability relative to PLC cycles matters more. Predictive models improve adaptation, yet only when their outputs are inserted into an already stable local execution structure. Semantic and rule layers improve interpretability, yet they function only when lower-level addressing and normalization remain consistent. Architectural stability, in other words, appears as a compound effect of separation and recombination. The layers are distinct. Their behavior is interdependent.

The analysis relied on comparative interpretation and synthesis throughout, though these methods were not used as detached procedural labels. Comparative reading allowed the identification of recurrent structural features across technically different implementations. Classification made it possible to distinguish field, PLC, gateway, supervisory, predictive, and semantic layers without reducing them to a rigid template. Synthesis then integrated these observations into a coherent explanatory model of PLC-based distributed energy management architecture. Interpretation remained necessary at each stage because many studies reported performance outcomes without fully articulating the internal control mechanism that produced them.

Several limitations should be acknowledged. The analysis relies on previously published studies. Differences in methodological design restrict direct comparison. Experimental conditions vary substantially, especially where laboratory SCADA prototypes, open-source monitoring systems, and full-scale energy platforms are considered together. Sample size remains deliberately selective rather than exhaustive, because the goal of the study is not bibliometric coverage but architectural explanation. At the same time, the reviewed literature reveals a

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consistent gap: while many studies explain what a system does, fewer explain how the internal architecture preserves coherence when signals, devices, and communication paths cease to behave uniformly. That gap justifies the present study.

III. RESULTS

The structural organization of distributed energy management systems implemented through programmable logic controllers reveals a persistent transition from isolated control loops toward interconnected operational layers, where field devices, controllers, and supervisory environments interact through continuously evolving data flows. At the lowest level, measurement infrastructures capture voltage, current, and thermal parameters through distributed sensing configurations that directly reflect the physical state of photovoltaic panels, storage systems, and loads. In one configuration, three voltage sensors and three current sensors are arranged to collect data simultaneously from the PV source, battery, and consumption nodes, forming a synchronized measurement environment that feeds directly into control execution (He et al., 2024). This arrangement reduces ambiguity in signal interpretation. The controller receives a coherent representation of system conditions.

Such coherence does not eliminate instability; it redefines its origin. The variability introduced by renewable generation shifts the burden of stabilization toward control architectures capable of continuous adjustment. Programmable logic controllers operate as deterministic cores within this structure, executing control routines independently of higher-level coordination. Their behavior is not static. It adapts through parameter updates received from supervisory layers. In practice, two temporal regimes emerge: high-frequency control loops maintain operational continuity, while slower analytical processes reshape system behavior through aggregated data and predictive insights (Melo et al., 2023). These regimes coexist without merging. Their interaction defines the architecture.

The integration of heterogeneous components forces architectural solutions to move beyond direct device compatibility. Photovoltaic inverters, storage systems, and grid interfaces operate under different protocols and internal logics, creating fragmentation at the communication level. Architectural patterns address this fragmentation through intermediate abstraction layers that transform device-specific signals into unified representations. These representations enable controllers to interpret system states independently of vendor-specific implementations, effectively decoupling control logic from hardware diversity (Veichtlbauer et al., 2021). Interoperability emerges not as a property of devices but as a property of the architecture.

Within this framework, data modeling becomes a stabilizing mechanism. Control-critical variables—such as relay activation thresholds or inverter setpoints—are processed within deterministic pathways, while telemetry data—such as consumption histories or environmental trends—flows through separate channels designed for aggregation and analysis. This separation prevents interference between control execution and data processing. It also enables scalability. Systems replicate more easily when data structures remain consistent across installations despite variations in equipment and configuration (He et al., 2024). Data uniformity supports architectural reproducibility. The systematization of architectural layers and their operational functions is presented below (Table 1).

Table 1. Functional structuring of PLC-based distributed energy management architectures (compiled by the author based on Melo et al., 2023; He et al., 2024 ; Veichtlbauer et al., 2021)

Architectural layer	**Main operational function**	**Typical signals / data objects**	**Engineering constraint**	**Architectural consequence**
Field device layer	Capture physical state and execute local actions	Voltage, current, temperature, relay status, inverter state	Heterogeneous interfaces and non-uniform update semantics	Need for signal validation before control admission

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PLC control layer	Execute deterministic control logic	Setpoints, thresholds, interlocks, mode variables	Real-time cycle stability and bounded latency	Separation of control-critical variables from telemetry flows
Gateway / protocol mediation layer	Translate device-specific communication into normalized exchange	Register maps, scaling rules, protocol objects, tag mappings	Protocol fragmentation and vendor-specific addressing	Use of abstraction and mapping tables
Supervisory layer	Aggregate states and coordinate multi-device behavior	Trends, alarms, mode commands, optimization inputs	Communication delay and limited timing suitability for fast loops	Redistribution of intelligence across temporal layers
Predictive / analytical layer	Process historical data and generate forward-looking adjustments	Forecast variables, learned patterns, transition conditions	Dependence on data quality and external computing resources	Partial externalization of decision preparation
Visualization / operator interface layer	Present interpreted system state and support intervention	Dashboards, alerts, manual override inputs	Need for coherent representation across subsystems	Consolidation of distributed states into a unified view
Semantic / rule layer	Formalize decision logic and cross-device coordination	Rules, dependencies, state-action relations	Requirement for stable meaning across heterogeneous devices	Declarative control structures and reusable logic

In practice, the coherence of control does not originate from the nominal consistency of device specifications, since field implementations frequently expose mismatches in register mapping, scaling factors, and update semantics across inverters, meters, and storage interfaces. Controllers are forced to interpret signals rather than simply consume them. This interpretation unfolds through validation layers embedded within the PLC logic, where incoming values are checked against expected physical ranges, temporal continuity, and cross-signal dependencies before being admitted into control loops. A current measurement that deviates from correlated voltage behavior is not immediately accepted. It is flagged, filtered, or temporarily substituted by last-known stable values. Such mechanisms are not auxiliary. They prevent propagation of erroneous states. At the same time, mapping tables translate vendor-specific registers into normalized variables, where units, sign conventions, and scaling coefficients are explicitly redefined within the control environment. The system does not assume correctness of input data. It reconstructs it. Control stability depends on this reconstruction.

Communication infrastructures introduce constraints that directly shape architectural decisions. The interaction between OPC UA servers and Modbus-based devices demonstrates measurable latency differences between control and supervisory layers. The time required for a request-response cycle at the OPC UA level exceeds the duration of a full acquisition cycle, which operates at 1.349 ms, indicating that supervisory communication cannot participate in real-time control loops without introducing delays (Ventuneac and Gaitan, 2024). This limitation forces systems to reorganize communication pathways. Lower-level devices exchange data directly through publisher–subscriber mechanisms operating at 12 Mb/s, bypassing higher-level layers whenever latency constraints require it (Ventuneac and Gaitan, 2024). Communication becomes selective. Only essential data traverses slower channels. The redistribution of

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communication and control functions is outlined below (Figure 1).

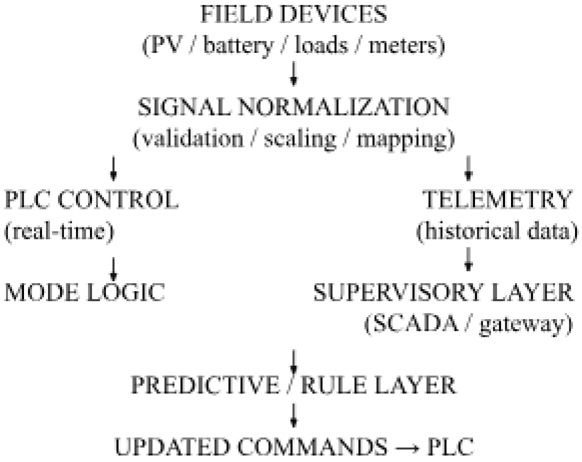

Fig.1. Simplified scheme of signal flow and control redistribution in PLC-based distributed energy management systems (compiled by the author based on Veichtlbauer et al., 2021; Ventuneac and Gaitan, 2024; Omidi et al., 2023; Melo et al., 2023)

Middleware selection further influences system behavior. Complex protocols provide extensive functionality but increase computational overhead, while lightweight alternatives reduce latency and simplify deployment. The substitution of OPC UA with MQTT in certain configurations demonstrates a reduction in execution time, allowing communication layers to operate within tighter temporal constraints and enabling deployment on simpler microcontrollers (Ventuneac and Gaitan, 2024). Architectural decisions reflect this trade-off. Simplicity enhances responsiveness.

Control logic evolves within these constraints toward mode-based operation. Systems do not rely on fixed rule sets; they operate through defined modes that describe coordinated states of all components. Transitions between modes determine how the system responds to changes in generation, consumption, and external constraints. Predictive extensions of this approach incorporate data-driven models that forecast system states and adjust transitions accordingly. In one implementation, predictive control based on LSTM models and hierarchical fuzzy logic reduced electricity consumption by 15% and operational costs by 24%, demonstrating the impact of anticipatory control on system performance (Gu et al., 2026). Prediction alters decision timing. Control becomes proactive.

The distribution of computational responsibilities reinforces this transformation. Predictive models are often executed in cloud environments, while PLCs maintain execution of deterministic control routines at the field level. This separation preserves real-time responsiveness while enabling advanced analytical capabilities. The architecture expands spatially. Control remains anchored locally.

Supervisory systems reflect similar patterns of modularization. Open-source SCADA architectures built on flow-based orchestration frameworks, including Node-RED-based implementations, distribute processing across interconnected nodes, each responsible for specific data transformations. Data collected from field devices is transmitted via MQTT, stored locally on platforms with 8 GB eMMC storage, and visualized through web-based interfaces, forming a continuous processing pipeline that integrates acquisition, storage, and visualization (Omidi et al., 2023). Each node performs a discrete operation. The system behaves as a chain of transformations.

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Energy management platforms extend these principles to system-wide coordination. Integrated environments combine generation units, storage systems, and consumption nodes within unified control frameworks capable of long-term optimization. In operational deployments, such platforms achieve measurable reductions in energy consumption. A decrease in total energy usage has been observed after implementing adaptive strategies based on simulation and real-time data analysis (Saeed et al., 2023). Efficiency emerges from coordinated adjustment. Isolated optimization plays a limited role.

Semantic rule-based control introduces an additional layer of interpretability. System behavior is encoded through formal rules that describe relationships between conditions and actions, allowing automated decision-making without direct human intervention. These rules enable flexible adaptation to changing system states while maintaining structural consistency across deployments (Rajendran et al., 2025; Veichtlbauer et al., 2021) Control logic becomes declarative. Execution follows interpretation. The differentiation of control modes and their operational behavior is presented below (Table 2).

Table 2. Functional differentiation of operating modes in PLC-based energy management systems (compiled by the author based on Melo et al., 2023; Gu et al., 2026; Rajendran et al., 2025; Veichtlbauer et al., 2021)

Operating mode	**Trigger condition**	**Control authority distribution**	**Signal handling characteristics**	**System behavior**	**Engineering implication**
Automatic mode	Stable input signals within predefined ranges	Distributed between PLC and supervisory layer	Continuous validation and normalized processing	Coordinated and optimized operation	Enables predictive adjustment and stable performance
Manual override	External operator intervention or supervisory command	Shift toward operator-controlled actions	Partial bypass of automated validation layers	Temporary deviation from optimized logic	Provides flexibility but reduces systemic coherence
Fault mode	Detection of abnormal signals or component failure	Localized within PLC with isolation of affected components	Filtering, substitution, or rejection of inconsistent data	Reduced functionality with maintained core operation	Ensures resilience under degraded conditions
Predictive-enhanced mode	Availability of historical data and forecasting inputs	Shared between predictive layer and PLC execution	Integration of forecast variables into control logic	Anticipatory adjustment of system states	Improves efficiency but introduces external dependencies
Communication-degraded mode	Loss or delay of supervisory communication	Fully localized at PLC level	Reliance on last valid or locally measured signals	Autonomous operation with reduced coordination	Preserves continuity under network constraints

Several limitations remain evident. Differences in hardware configurations, communication protocols, and data modeling approaches restrict direct comparability between implementations. Laboratory validation does not fully reproduce operational variability. Predictive

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models depend on the availability and quality of historical data, while distributed architectures introduce dependencies on external computational resources. These constraints do not invalidate observed patterns. They define their boundaries.

Architectural configurations do not converge toward a single dominant structure. They evolve under the influence of heterogeneity, latency constraints, and operational uncertainty. Control systems reorganize continuously. Stability is achieved through structural adaptation rather than uniform design.

IV. DISCUSSION

Stability in distributed energy management systems emerges under conditions where electrical generation, storage behavior, and consumption profiles evolve asynchronously, producing continuous fluctuations that propagate through control infrastructures. These fluctuations do not destabilize the system by themselves. They expose the limits of static coordination. Control architectures respond by restructuring signal interpretation into layered processes, where measurement, normalization, and execution form a closed operational loop. Raw electrical parameters are not directly actionable. They are transformed into structured variables aligned with operational constraints. The controller does not react to signals as they arrive. It reacts to interpreted states.

This distinction becomes more visible when grid constraints impose explicit limits on system behavior. Export-limiting introduces a condition in which internal energy balance must be preserved while external power exchange remains bounded. The mechanism does not rely on a single controlling entity. Instead, multiple converters and storage units adjust their outputs simultaneously through coordinated setpoint redistribution. Each component evaluates its local state and modifies its contribution relative to a shared constraint. A surplus at one node does not propagate outward. It is absorbed internally. The system redistributes energy before it exports it.

Such redistribution depends on the ability of control systems to operate across multiple temporal layers. Immediate adjustments occur within deterministic PLC cycles, where control logic executes without dependency on supervisory feedback. At the same time, supervisory environments process aggregated data and update coordination strategies over longer intervals. These layers do not converge into a unified control loop. They overlap. One maintains continuity. The other reshapes behavior.

Operating modes structure this interaction by defining how control authority is distributed under different conditions. Automatic operation maintains coordinated behavior when system inputs remain within expected ranges, allowing predictive inputs and real-time measurements to guide decisions. Manual override interrupts this continuity, shifting control authority toward external operators and temporarily isolating automated routines. Fault-handling modes reorganize system structure under degraded conditions, where certain components become unavailable or unreliable. The system does not attempt to preserve its original configuration. It redefines it. Control logic adapts by isolating faulty segments and maintaining minimal operational coherence. Functionality contracts. Execution continues.

Communication infrastructures influence these transitions more directly than their supporting role suggests. Signal exchange depends not only on protocol compatibility but on temporal alignment between communication cycles and control execution. When latency exceeds control cycle duration, supervisory coordination cannot participate in real-time decision-making. Control logic withdraws to local execution. Visibility decreases. Operation persists. Communication failures do not stop the system. They reduce its awareness.

This behavior explains the increasing reliance on intermediate layers that normalize communication across heterogeneous devices. Previous research often frames interoperability as a technical problem of protocol alignment, emphasizing standardization of interfaces. In practice, systems operate through semantic translation, where signals are mapped into unified representations before being processed by control logic. Devices do not need to share protocols. They need to share meaning. Gateways and abstraction

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layers perform this translation, converting device-specific outputs into standardized variables that retain consistent interpretation across the system. Architectural coherence depends on this transformation.

Data modeling reinforces this mechanism by structuring how information is organized and processed. Signal normalization defines units, scaling factors, and identifiers that allow heterogeneous inputs to be interpreted consistently. Addressing schemes and namespace hierarchies position each variable within a defined structure, ensuring that control logic accesses data without ambiguity. Control-critical signals follow deterministic pathways with strict timing constraints, while telemetry data accumulates in parallel channels designed for analysis and optimization. These pathways remain separate. Interference is avoided. The system processes what is urgent first. Everything else follows.

Commissioning procedures reveal how these structures behave under controlled validation. Communication testing establishes connectivity and identifies protocol inconsistencies at early stages. Signal verification confirms that measured values correspond to physical conditions and that normalization parameters are correctly applied. Logic simulation introduces artificial scenarios that test control routines without affecting physical processes, exposing inconsistencies in mode transitions and coordination strategies. Live validation follows, where the system operates under real conditions and its responses are observed. Each stage isolates a different layer of the architecture. Failures are not random. They reflect structural misalignment.

Comparative observations from prior implementations indicate that architectural evolution does not proceed toward centralization. Earlier systems concentrated decision-making within supervisory layers, relying on centralized coordination to manage distributed components. More recent configurations redistribute intelligence, allowing local controllers to execute critical operations independently while supervisory systems provide optimization and strategic adjustment. Predictive models extend this redistribution by introducing temporal anticipation into decision-making processes. Control systems begin to operate ahead of observed states. Reaction shifts toward preparation.

This shift introduces new dependencies that reshape system resilience. Predictive control relies on historical datasets and computational resources that may not always be available. When these inputs degrade, predictive layers lose effectiveness, and control reverts to reactive operation. The system does not fail. It simplifies. Performance changes, but functionality remains intact. Deterministic control layers continue to operate independently of predictive components.

Several limitations should be acknowledged. The analysis relies on previously published studies with heterogeneous experimental setups, varying hardware configurations, and different communication protocols, which restrict direct comparability. Observations derived from controlled environments do not fully capture the variability present in real-world deployments, where environmental conditions and operational disturbances introduce additional complexity. Data-driven approaches depend on the availability and consistency of historical datasets, which differ across installations. Communication infrastructures exhibit variable reliability, influencing system behavior in ways that remain difficult to standardize.

V. CONCLUSION

The first research objective concerned the redistribution of control responsibilities across operational layers. The analysis shows that PLC-based distributed energy management systems preserve stability by dividing execution into temporally distinct yet interacting domains. Deterministic PLC loops process urgent control actions locally, while supervisory and predictive environments reshape parameters, coordination logic, and longer-horizon responses. These layers do not merge into one universal controller. They remain differentiated. Stability depends on that differentiation.

The second objective focused on the transformation of heterogeneous signals into unified control variables. The study demonstrates that interoperability is sustained not merely through

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protocol connectivity but through signal normalization, mapping, validation, and semantic reinterpretation. Field values are checked, reconstructed, and translated before they are admitted into control loops. This mechanism explains why scalable deployment becomes possible even when devices differ in addressing logic, scaling factors, and update behavior. The architecture processes inconsistency instead of ignoring it.

The third objective addressed the influence of mode-based logic, communication constraints, and predictive extensions on operational behavior. Here the analysis indicates that operating modes restructure control authority under changing conditions, while communication limitations impose boundaries on what supervisory coordination can realistically influence in real time. Predictive layers improve responsiveness and energy performance, but they do so by modifying transitions and setpoints around a persistent local control core. They extend the architecture. They do not replace it.

The hypothesis is supported. Stable operation in PLC-based distributed energy management systems does not arise from homogeneity of components. It arises from layered organization of interpretation, execution, mediation, and adaptation. When those layers are coherently arranged, the system remains controllable under latency, variability, export constraints, and partial degradation.

Several limitations remain. The analysis relies on heterogeneous prior studies, and real installations still differ in communication quality, device behavior, and data availability. Yet one conclusion remains difficult to avoid: these systems do not stay stable because uncertainty disappears. They stay stable because the architecture learns to contain it. Control persists. The structure changes first.

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