Intelligence Modeling in Electromechanical Systems

www.imes.reapress.com

Intell. Model. Electromech. Syst. Vol. 2, No. 2 (2025) 95–110.

Paper Type: Original Article

A Holonic-Based Decentralized Framework for Optimal Reactive Power Control in Smart Grids

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Citation:

Received: 11 April 2024 *Revised: 18 May 2024* *Accepted: 29 October 2024*	Ahmadzadeh, M., Bahadori, A., & Fazeli, R. (2025). A holonic-based decentralized framework for optimal reactive power control in smart grids. *Intelligence modeling in electromechanical systems,* 2(1), 95-110.

Abstract

Monitoring power systems serves as the foundational requirement for making informed decisions in control centers. In recent years, the emergence of smart grids has propelled reactive power control and power system monitoring into a new phase. This development has highlighted the urgent need for efficient and Decentralized Optimal Reactive Power Control (DORPC) methods, especially within frameworks that align with smart grid technologies. This paper introduces a novel DORPC approach based on a holonic architecture, featuring a unique hierarchical design. The main goal is to show that individual DORPC agents can attain global optimality through local interactions. The proposed method is compared with two benchmark techniques using a comprehensive array of performance metrics. The findings reveal that this approach holds considerable promise for reducing active power losses, maximizing the utilization of reactive power resources, relying on a minimal data set, and improving network fault tolerance.

Keywords: Smart grid, Decentralized optimal reactive power control, Holonic architecture, Reactive power management, Active power loss minimization, Fault tolerance.

1 | Introduction

The increasing penetration of Distributed Energy Resources (DERs) in modern distribution networks has introduced considerable challenges for reactive power control [1]. At the same time, the evolution toward smart grids signifies a fundamental transformation in power system operation and management. One of the essential enablers of these emerging systems is the deployment of distributed control algorithms that rely on continuous data exchange among multiple intelligent agents [1].

Historically, power systems have been operated under centralized control structures, where a supervisory control center—typically supported by SCADA systems—collects measurements across the network to coordinate system-wide operation [2]. While this architecture has proven effective for traditional grids, it becomes increasingly inefficient and fragile as the number of sensors, actuators, and DERs grows. Centralized approaches impose substantial computational and communication burdens, leading to network congestion and higher exposure to communication failures or interference [2].

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https://doi.org/10.48314/imes.vi.33

Furthermore, centralized control frameworks depend heavily on the availability and reliability of a single processing center. This dependence creates vulnerability to single-point failures, which can severely disrupt control performance if a communication link or central processor fails. In contrast, decentralized control architectures enhance operational resilience, improve data accessibility, and provide greater flexibility for real-time decision-making in smart grid environments [1], [3].

Reactive power control remains one of the most critical aspects of power system operation. Inadequate reactive power support has been identified as a major contributor to voltage instability and large-scale blackouts in recent decades [4]. The Optimal Reactive Power Control (ORPC) problem seeks to identify the optimal configuration of control variables—such as generator terminal voltages, transformer tap changer positions, and reactive power outputs of compensating devices and Distributed Generators (DGs)—to minimize Objective Functions (OFs) (typically active power losses) while satisfying operational and physical constraints [5]. From a computational standpoint, ORPC represents a nonlinear and constrained optimization problem whose key goals include minimizing power losses, reducing voltage deviations, and improving voltage stability margins [5].

Several approaches have been proposed to address the multi-objective nature of the reactive power control problem. In [5], a method is introduced that considers constraints on bus voltage limits, branch power flow limits, generator voltages, transformer tap positions, and reactive power compensation levels at weak buses, aiming to minimize both active power losses and voltage deviations [6]. Likewise, the studies in [4], [7] present probabilistic multi-objective optimization frameworks for reactive power management in electricity markets, accounting for uncertainties associated with load forecasting. These works leverage smart grid technologies, particularly Advanced Metering Infrastructure (AMI), to enable secure data acquisition and propose hierarchical Intelligent Control System (ICS) structures with centralized and local layers to facilitate real-time reactive power management at the consumer level.

In a decentralized context, the works in [8], [9] authorize agents to independently determine reactive power injections within the network. Guerrero et al. [10] propose a non-centralized, predominantly offline coordination approach for optimizing reactive power setpoints of DGs. Similarly, Antoniadou-Plytaria et al. [11] introduces a decentralized voltage control algorithm designed for loss minimization without requiring detailed system models, maintaining robust performance even under microgrid reconfiguration or islanded operation. A distributed multi-agent reactive power management scheme for smart distribution systems is also presented in [12], where the global optimization problem is decomposed into smaller subproblems, each managed by an autonomous agent to enhance system scalability and resilience.

The main objective of this paper is to develop a Decentralized Optimal Reactive Power Control (DORPC) framework tailored for smart grids. The proposed method leverages a holonic architecture, enabling agents to act both autonomously and cooperatively to achieve system-wide optimization objectives. This architecture allows operators to maintain the grid closer to its optimal operating point while mitigating the inherent limitations of centralized approaches. By exploiting two core features of the holonic paradigm—dynamic reconfiguration and negotiation mechanisms—the proposed framework ensures effective utilization of available reactive power resources, even in the presence of uncertainties associated with renewable energy sources.

To validate the proposed approach, the DORPC framework is benchmarked against two existing methods and evaluated through a detailed case study in a smart grid environment. Building upon our previous work on decentralized reactive power dispatch [13], this study demonstrates the enhanced performance, robustness, and adaptability of the proposed method. The key contributions of this paper are summarized as follows:

I. Development of a hierarchical and fully decentralized approach for reactive power flow management.
II. Introduction of a communication-efficient strategy that minimizes redundant data exchange among system agents.
III. Proposal of a real-time DORPC method requiring minimal coordination and computational resources.

IV. Implementation of a flexible simulation testbed for performance validation, using the Java Agent Development Framework (JADE) integrated with MATLAB to enable realistic experimental evaluation

2 | Holonic Systems: Concept and Characteristics

The concept of a holon was first introduced by the Hungarian philosopher Arthur Koestler to describe self-similar and recursive structures observed in social and biological organizations [14]. A holon is defined as a stable, integrated, and self-similar fractal entity that may consist of smaller holons (sub-holons) and, in turn, form part of a larger holon (super-holon). Depending on the level of abstraction, a holon can function as an autonomous atomic entity, a dependent component within a larger organization, or as a multi-layered structure encompassing several hierarchical levels. Collectively, holons create a recursive hierarchy, where each level is composed of interrelated holons that preserve both autonomy and coherence across the organizational structure [15], [16].

A holon typically exhibits several fundamental characteristics [15], [16]:

I. Autonomy (computational independence): each agent possesses the capability to control its own actions and decisions without direct human intervention, ensuring local independence.

II. Cooperative behavior: all sub-holons pursue at least one shared objective in addition to their individual goals, facilitating coordination toward a common system purpose.

III. Scalability: holons demonstrate the ability to achieve collective behaviors at the group level that individual entities cannot accomplish alone—that is, a super-holon can exhibit functionalities beyond the aggregate sum of its sub-holons.

IV. Transparency: agents maintain an explicit representation of their environment, ensuring that system-level trust and visibility are preserved throughout the hierarchy.

V. Bounded rationality: each holon must act rationally within the limits imposed by its objectives, available resources, and environmental conditions.

VI. Communication: communication is vital to sustaining autonomy and coordination. In holonic architectures, interactions occur both vertically—between a head holon and its sub-holons for supervision—and horizontally—among peer holons for cooperation and negotiation [17].

In general, holonic Multi-Agent Systems (MAS) model organizational interactions through the Role–Interaction–Organization (RIO) framework [15], [17]. This model provides a conceptual foundation for defining how individual agents contribute to the overall organizational behavior.

I. Roles specify the expected patterns of behavior and responsibilities assigned to agents.

II. Interactions describe the dynamic exchanges that occur among agents to achieve these roles.

III. Organizations emerge as structured entities resulting from the coordination of roles and interactions.

Within this framework, organizational behavior is classified and managed through a unified structural model. Two primary approaches have been proposed for modeling holonic structures based on the RIO framework: holonic organization models and goal-oriented interaction models. These models provide complementary perspectives for designing scalable, adaptive, and cooperative agent-based systems capable of addressing complex control and optimization challenges in modern power networks

3 | Holonic Structural Organization

Holons are internally organized into higher-level entities, referred to as super-holons, through three distinct management structures: independent group, moderated group, and integrated group [15], [16]. Among these, the moderated group structure is adopted in this study to provide organizational flexibility across diverse system configurations. This structure allows sub-holons to dynamically associate with or disengage from super-holons according to evolving operational requirements and contextual obligations. A schematic representation of sub-holon autonomy levels is presented in *Fig. 1*.

Within the moderated group structure, sub-holons operate under two fundamental states:

I. Connection with a supervising holon, where they function under the guidance or coordination of a higher-level entity.

II. Representation by supervisors, in which supervisory holons act as intermediaries to facilitate coordination and communication within the hierarchy.

To support these operational modes, four distinct roles are defined within each holonic organization: head, multi-part, part, and non-member. The head role corresponds to the supervisory holon within a super-holon, responsible for coordination and decision-making. The multi-part and part roles represent member holons: a multi-part holon participates simultaneously in multiple holonic groups, enabling inter-holon collaboration, while a part holon is affiliated with only one super-holon, maintaining a single chain of authority. Non-member holons are external entities that may engage in negotiation or information exchange with head holons to establish temporary or permanent affiliations. Such holons can issue service requests or respond to supervisory commands depending on the coordination mechanism in place. A schematic illustration of the holonic role hierarchy and their interactions is shown in *Fig. 2*, depicting the flow of authority, communication, and collaboration among various holon types. This structural flexibility supports adaptive coordination and enhances scalability key properties required for managing complex, distributed systems such as modern power grids.

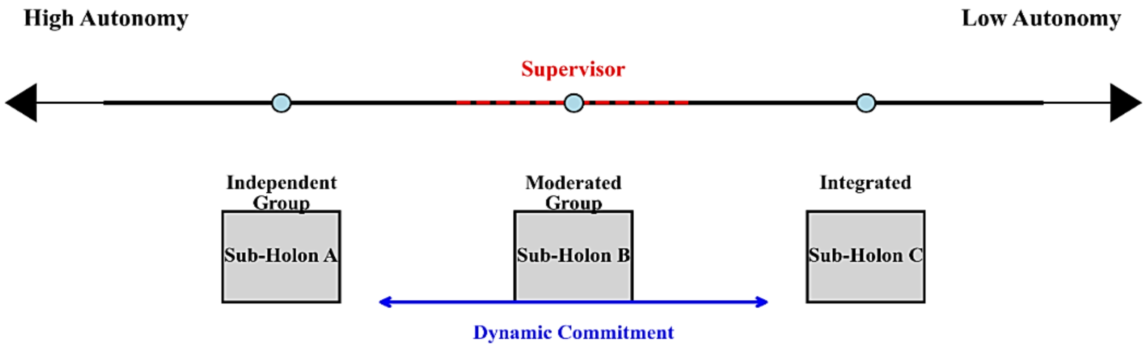


Fig. 1. Autonomy level of sub-holons in moderated group structure.

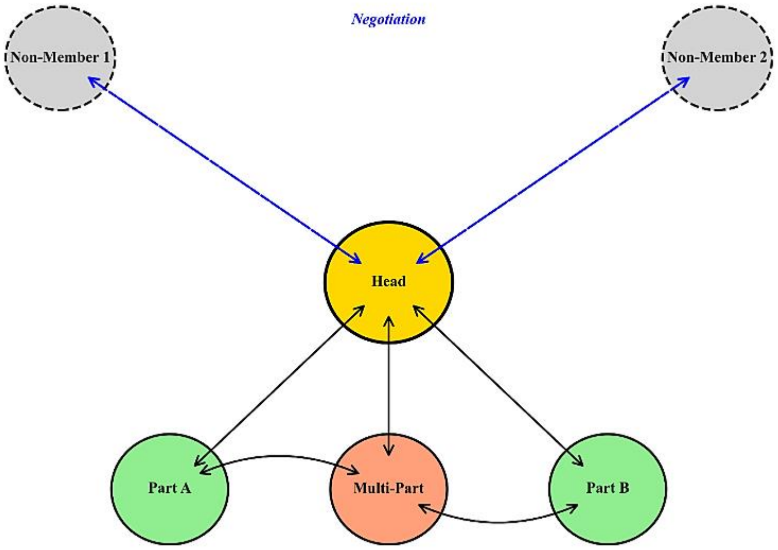


Fig. 2. Schematic of holonic rule.

Table 1. Holonic rules and their characteristics [15], [17].

Data Type	Dataset Size	Depth (Layers)	Width (Neurons/Layer)	Activation
Image (e.g., CIFAR, ImageNet)	Small (< 10k)	3-5	64-128	ReLU / Leaky ReLU
	Medium ($10\mathrm{k}-1\mathrm{M}$)	10-20	128-512	ReLU / Leaky ReLU
	Large ($>1\mathrm{M}$)	20-50	256-1024	ReLU / GELU
Text / NLP (sequence data)	Small	2-3 (RNN/LSTM layers)	128-256	Tanh / ReLU
	Medium	3-6	256-512	ReLU / GELU
	Large	6-12	512-1024	GELU / ReLU
Tabular / Structured Data	Small	2-3	32-128	ReLU / Leaky ReLU
	Medium	3-5	64-256	ReLU / Leaky ReLU
	Large	5-10	128-512	ReLU / GELU
Time Series / Forecasting	Small	1-2 (RNN/GRU/LSTM)	64-128	Tanh / ReLU
	Medium	2-4	128-256	ReLU / GELU
	Large	4-8	256-512	ReLU / GELU
Medical Imaging (MRI, CT, X-ray)	Small ($<5\mathrm{k}$)	3-5	32-128	ReLU/Leaky ReLU
	Medium (5k-50k)	8-20	128-512	ReLU / GELU
	Large ($>50\mathrm{k}$)	20-50	256-1024	ReLU / GELU
Genomic / High-Dimensional Omics Data	Small (< 1k)	2-3	64-128	ReLU / Leaky ReLU
	Medium ($1\mathrm{k}-10\mathrm{k}$)	3-6	128-256	ReLU / GELU
	Large ($>10\mathrm{k}$)	6-12	256-512	ReLU / GELU
Electronic Health Records / Tabular Medical Data	Small	2-3	32-128	ReLU / Leaky ReLU
	Medium	3-5	64-256	ReLU / GELU
	Large	5-10	128-512	ReLU / GELU

4 | Goal-Oriented Interactions in Holonic Structures

Defining and managing interactions among group members is a fundamental aspect of holonic systems that has often been underexplored in the existing literature. These interactions, referred to as goal-oriented interactions (also known as goal-driven or goal-directed interactions), play a crucial role in achieving coherent system behavior. Each holon performs a set of specific actions designed to fulfill its individual and collective objectives. Consequently, an internal organizational framework built upon goal-oriented interactions must facilitate efficient information exchange among non-atomic sub-holons to ensure coordinated goal attainment.

Within this framework, the holonic system can be conceptually divided into two primary components:

I. Individual instance: this represents a unique organizational configuration corresponding to a specific holonic group. All members of a holon or super-holon belong to this organizational instance, which defines their structural and functional relationships.

II. Set of internal organizational instances: these consist of smaller, task-oriented groups formed based on shared objectives and operational dependencies. Their main purpose is to coordinate the interactions required to achieve the super-holon's overarching goals. Each such group may comprise only a subset of the super-holon's members, enabling flexible and adaptive coordination at different hierarchical levels.

The internal organization and the flow of goal-oriented interactions are schematically depicted in *Fig. 3*, which illustrates how sub-holons exchange information and align their local objectives with the global mission of the super-holon. This structural abstraction enhances the adaptability, robustness, and scalability of holonic MAS, making them particularly suitable for applications in dynamic and distributed environments such as smart grids.

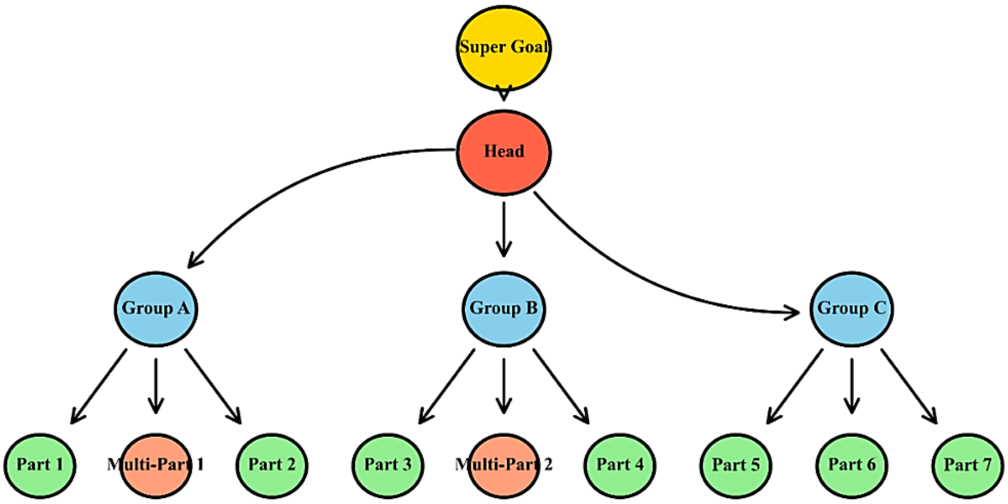


Fig. 3. Goal oriented interaction in holonic framework.

5 | Self-Organization and Adaptive Role Dynamics in Holonic Systems

As discussed earlier, the components of a holonic system represent the current operational state of its constituent elements, while the transfer of roles among them plays a pivotal role within a super-holon. These dynamic roles allow the holonic structure to continuously adapt to changing system conditions. Role reconfiguration is a core mechanism of self-organization, enabling roles—such as the head role—to be reassigned to other holons depending on the system's state or performance requirements. This dynamic reassignment significantly enhances both the flexibility and adaptability of individual holons, allowing the overall structure to maintain stability while responding effectively to disturbances or evolving objectives.

From a foundational standpoint, each holon exhibits two essential capabilities that underpin its self-adaptive behavior:

I. Compatibility: two holons are considered compatible when they share a common objective or when their goals are mutually supportive. Compatibility determines the potential for cooperative interaction within the holonic network.

II. Dependency: this property, expressed in terms of satisfaction [17], quantifies how effectively two holons can collaborate toward achieving a shared goal. Dependency thus provides a measure of inter-holon synergy.

The satisfaction of a holon is defined relative to its own objectives and can be classified into four distinct categories, depending on the nature of its interactions with other agents:

I. Self-Satisfaction (SS): represents the degree to which a holon fulfills its objectives independently, without external cooperation.

II. Cooperative Satisfaction (CS): achieved when a holon attains its goals through collaborative interactions with other holons within the same hierarchy.

III. Aggregate Satisfaction (AS): evaluates the combined level of satisfaction resulting from cooperation among multiple holons within a super-holon, reflecting collective performance.

IV. Instantaneous Satisfaction (IS): refers to the immediate level of satisfaction corresponding to the holon's current operational state or decision context.

These satisfaction metrics form the basis for the quantitative assessment of adaptation and coordination in holonic systems. Formal mathematical definitions and formulations of these metrics are provided in the following subsections.

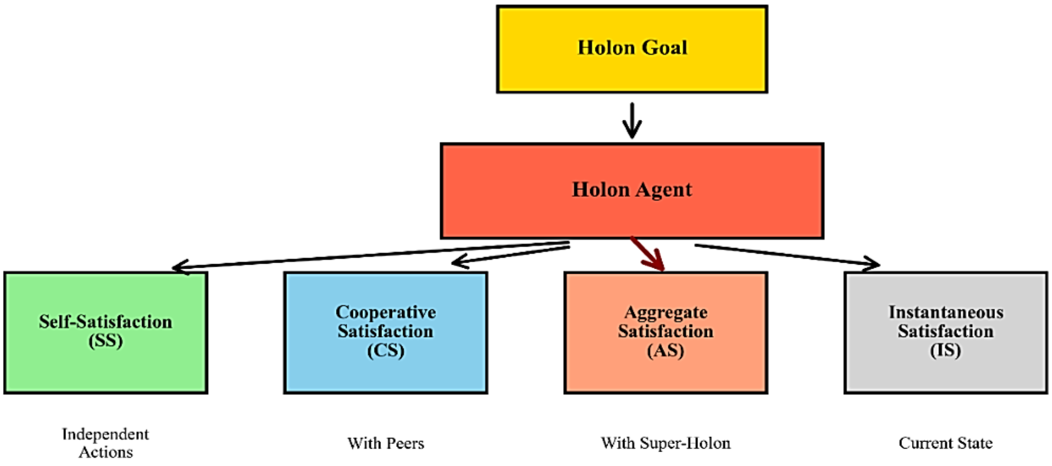


Fig. 4. Types of satisfaction in holonic self organization [17].

6 | Holonic-Based Architecture for Decentralized Optimal Reactive Power Control

This paper proposes a comprehensive organizational architecture that integrates the principles of MAS and is tailored to the objectives of smart grids. At the outset, it is crucial to distinguish between two complementary aspects: the holon-based structural organization and the goal-dependent internal organization. In the proposed framework, the smart grid is partitioned into sub-holons that collectively form a holon, while each holon may simultaneously participate as a component of a higher-level super-holon, creating a hierarchical and self-similar network structure.

At the lowest hierarchical level, atomic holons represent fundamental entities such as loads, DERs, and controllable devices. Designing an appropriate holonic structure to integrate diverse smart grid functionalities—such as distributed generation management, microgrid operation, Demand Response (DR), demand-side management, frequency control, and voltage regulation—poses a significant challenge. Existing approaches often address these functionalities in isolation through hybrid solutions, which may not scale efficiently or generalize across different operational scenarios.

The core contribution of this work is the introduction of a holonic organized multi-agent system that unifies both structural and functional aspects of smart grids. This framework is applied primarily to the DORPC problem; however, its generality allows extension to other operational domains within power system management. Notably, the integration of structural and functional perspectives within a single holonic architecture addresses a gap largely overlooked in prior literature.

Given the inherent complexity of smart grids, which comprise numerous interacting components, analyzing the system at a global scale can be computationally challenging. To mitigate this, the proposed approach segments the network into smaller management zones, referred to as views. Each view corresponds to a specific system segment, within which a holon is defined to manage both its structure and behavior. Constructing a holon within a view requires consideration of two interrelated perspectives:

I. Structural perspective (holonic organization): examines the composition of the holon and its constituent sub-holons within the defined view, ensuring a coherent hierarchical arrangement.

II. Behavioral perspective (goal-dependent internal organization): evaluates the holon's dynamic behavior, taking into account its roles, interactions, and internal organizational dynamics to achieve defined objectives.

For instance, in the context of DORPC, a distribution feeder can be modeled as a holon, where its operational behavior is analyzed and coordinated according to the holonic framework. This approach allows localized management while maintaining alignment with global system goals, thereby enhancing both efficiency and adaptability in reactive power control.

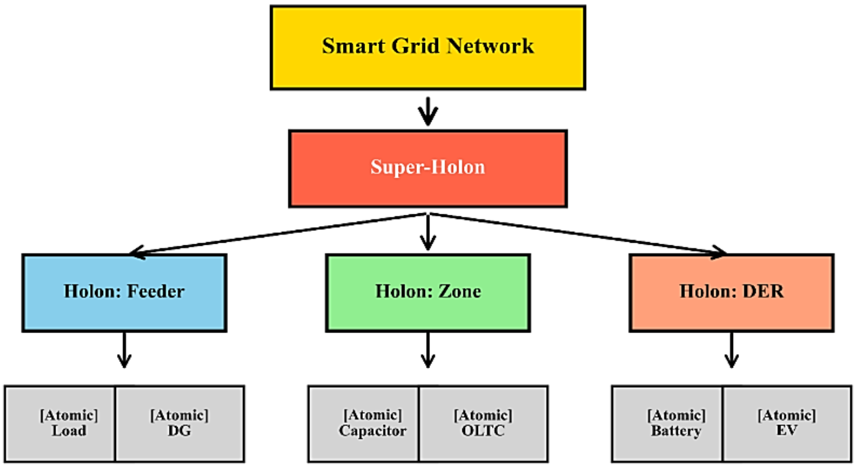


Fig. 5. Holonic decomposition of a smart grid feeder for DORPC.

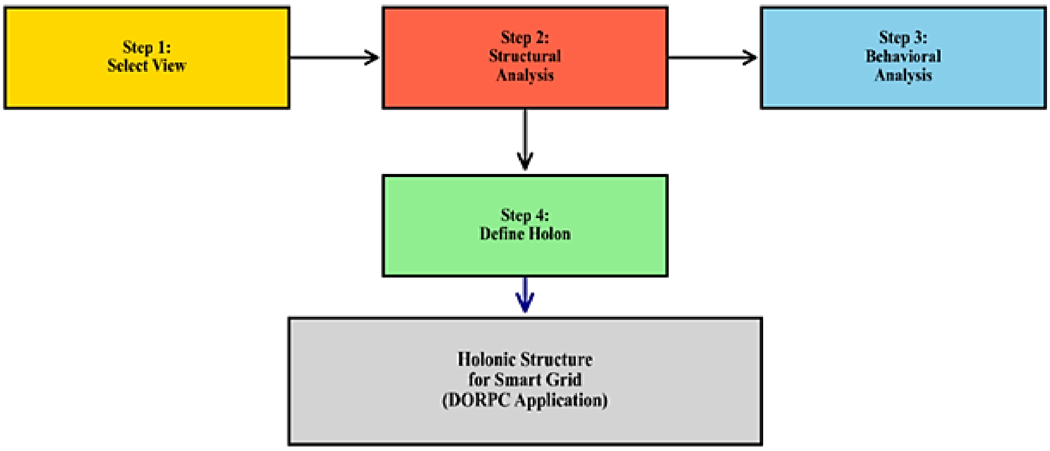


Fig. 6. Process of defining holonic structure for smart grid.

Based on the holon concept, the smallest super-holon at the top level of a smart grid can represent a household, encompassing atomic sub-holons such as loads, DGs, smart appliances, smart plugs, Programmable Communicating Thermostats (PCTs), Plug-in Electric Vehicles (PEVs), transformers, and other components. In this study, these low-voltage-level super-holons are referred to as Low-Voltage Transformer Holons (LVT-Holons). Each LVT-Holon aggregates atomic holons, including smart homes, energy resources (e.g., capacitors or DGs), controllable devices such as tap changers, and AMI.

At this level, large-scale resources—such as smart parking lots [6] or substantial reactive power sources—are treated as separate holons and are not included within industrial customer holons. Moving to a higher hierarchy, holons associated with a Medium-Voltage (MV) feeder, including LVT-Holons, DG-Holons, or other reactive power source holons, are collectively termed Medium-Voltage Feeder Holons (MVF-Holons).

Each MVF-Holon supervises a segment of the MV feeder, providing coordinated control and management of its sub-holons.

Multiple MVF-Holons may combine to form a higher-level holon known as a Medium-Voltage Transformer Holon (MVT-Holon), which manages an entire MV feeder. The MVT-Holon encompasses sub-holons such as tap changers, AMI measurement units, and other control devices, enabling integrated monitoring and control.

At an even higher hierarchical level, a Distribution Holon (D-Holon) is defined as a super-holon comprising multiple MVF-Holons, providing centralized oversight over broader distribution segments. Finally, at the High-Voltage (HV) level, D-Holons are integrated into a High-Voltage Holon (HV-Holon), establishing a fully hierarchical, multi-level holonic representation of the smart grid.

This hierarchical structuring of holons ensures scalability, adaptability, and coordination across all voltage levels, enabling the distributed management of both conventional and renewable energy resources while maintaining system-wide operational objectives

7 | Energy Management System in Holonic Architecture

At the highest hierarchical level, the Energy Management System (EMS) is represented as a holon, referred to as the EMS-Holon. Unlike traditional Information and Control Systems (ICS), in this decentralized framework, all data and command exchanges are not required to pass through the EMS [7]. Instead, individual holons can directly negotiate with one another to optimize their internal organization and monitor performance autonomously, enhancing flexibility and reducing Communication Overhead (OAT).

Interaction with higher-level holons occurs only when lower-level actions—including negotiation outcomes, holon reconfiguration, or local control adjustments—are insufficient to meet operational requirements. In such scenarios, the lower-level holon submits a request to its immediate supervisor. The supervising holon evaluates the situation, makes decisions, and, if necessary, negotiates with peer holons at the same level to facilitate collaborative control. If the issue persists, the request escalates through the hierarchical structure until it is resolved by the EMS-Holon.

This hierarchical, decentralized approach substantially reduces redundant data exchanges, minimizes communication bandwidth requirements, and accelerates decision-making by localizing most computations. Consequently, computational latency is reduced, resulting in faster response times and enhanced system stability. A schematic representation of this hierarchical control structure is illustrated in *Fig. 5*.

For example, a Low-Voltage Transformer Holon (LVT-Holon) communicates with its supervising holon—either another LVT-Holon or a MVF-Holon—while managing its internal interactions to achieve its objectives. In this study, the OF, defined in [10], serves as the utility function for holons, although it can be extended to other operational goals within the power system.

When an LVT-Holon cannot satisfy its operational constraints using local resources, it negotiates with its supervisor or neighboring holons at the same level, as described in *Figs 3-7*. Negotiations may involve multiple issues, including the allocation or transfer of reactive power resources, as defined in *Fig. 7*. Sub-holons may temporarily join neighboring holons for collaborative control, or negotiate the redistribution of reactive power to balance system requirements.

This dynamic behavior exemplifies the key advantage of holonic structures: adaptive, decentralized, and cooperative control. The same framework can be applied to higher voltage levels, including the transmission system (HV), enabling a fully hierarchical and decentralized structure that addresses diverse operational objectives across the entire smart grid.

8 | Case Study Implementation and Simulation Results

To evaluate the effectiveness of the proposed strategy, a transmission system interconnected with four distribution systems is considered. The holonic model is applied to 6 load buses and 33 transmission lines, forming the testbed for the study.

In this case study, the holonic-based DORPC strategy is implemented with several key components modeled as holons, including distribution transformers, tap changers, conventional generators, DGs, and shunt capacitors. The DG units consist of Photovoltaic (PV) and Wind Turbine (WT) systems, with their locations and rated capacities detailed in *Table 2*. All shunt capacitors are assumed to have 10 discrete steps, while the PV and WT units are simulated with hourly reactive power margins calculated based on active power output and rated capacity. Technical specifications for wind farms, solar farms, and PEVs are summarized in *Table 3*. Using the proposed DORPC strategy, MVF-Holons optimally leverage their local reactive power resources to minimize the OF according to internal priorities and negotiation outcomes. The resulting voltage profile for the IEEE 33-bus distribution system is presented in *Fig. 7*, demonstrating that the proposed DORPC maintains voltage magnitudes within acceptable operational limits.

As highlighted in previous sections, holons can utilize both local resources and resources from neighboring holons through negotiation. This distributed decision-making framework enhances the utilization of available reactive power across the network. Each holon seeks to minimize its OF by optimally dispatching local reactive power while respecting operational constraints. When constraints are violated or when accessing neighboring resources provides a more cost-effective solution, holons negotiate with adjacent or higher-level holons to redistribute resources efficiently. *Figs. 8(a)–(d)* illustrate the temporal evolution of decision variables in the IEEE 33-bus system. Capacitor step changes are particularly pronounced during peak hours, reflecting holons' adaptive adjustments when the system approaches critical operating points. Furthermore, as shown in *Fig. 8(f)*, the reactive power output of PV units decreases during midday due to high active power generation, whereas it increases during morning and evening periods when active power output declines. A similar pattern is observed for WTs, consistent with prevailing wind speed profiles. These results highlight the effectiveness of the holonic DORPC framework in coordinating distributed reactive power resources, ensuring voltage stability, and dynamically adapting to variations in renewable generation and load demand.

Table 2. DG and capacitor locations and capacities.

Bus	DG Type	Capacity (MW)	Capacitor (kVAR)
6	PV	1.5	300
12	WT	2.0	400

Table 3. Technical data for wind, solar, and PEVs.

Resource	Rated Power (MW)	Location	Efficiency (%)
Wind farm	5.0	Bus 18	92
Solar farm	3.0	Bus 25	18
PEV cluster	1.2	Bus 33	95

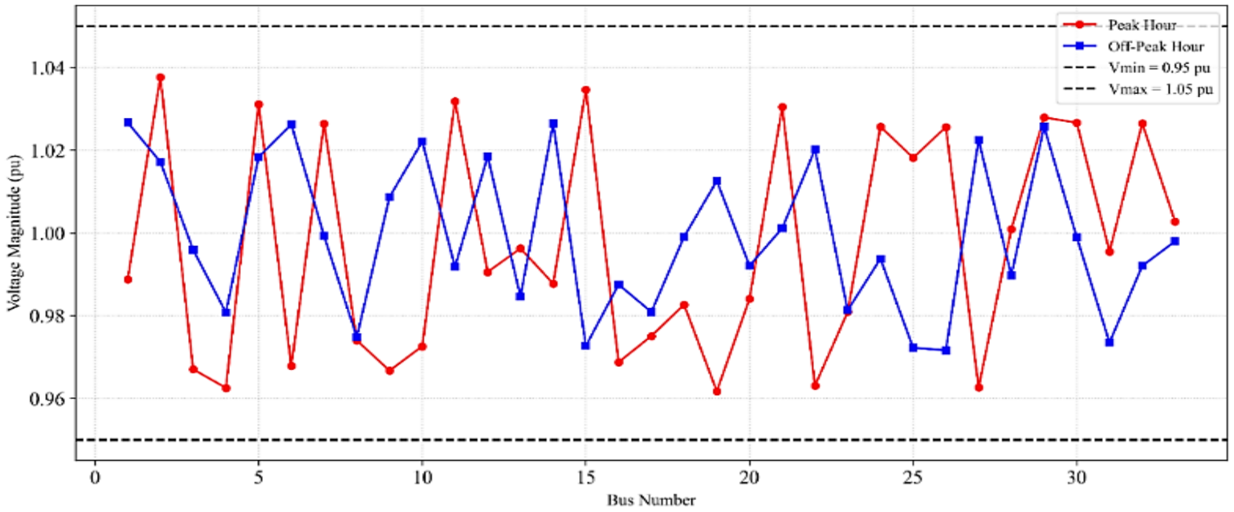
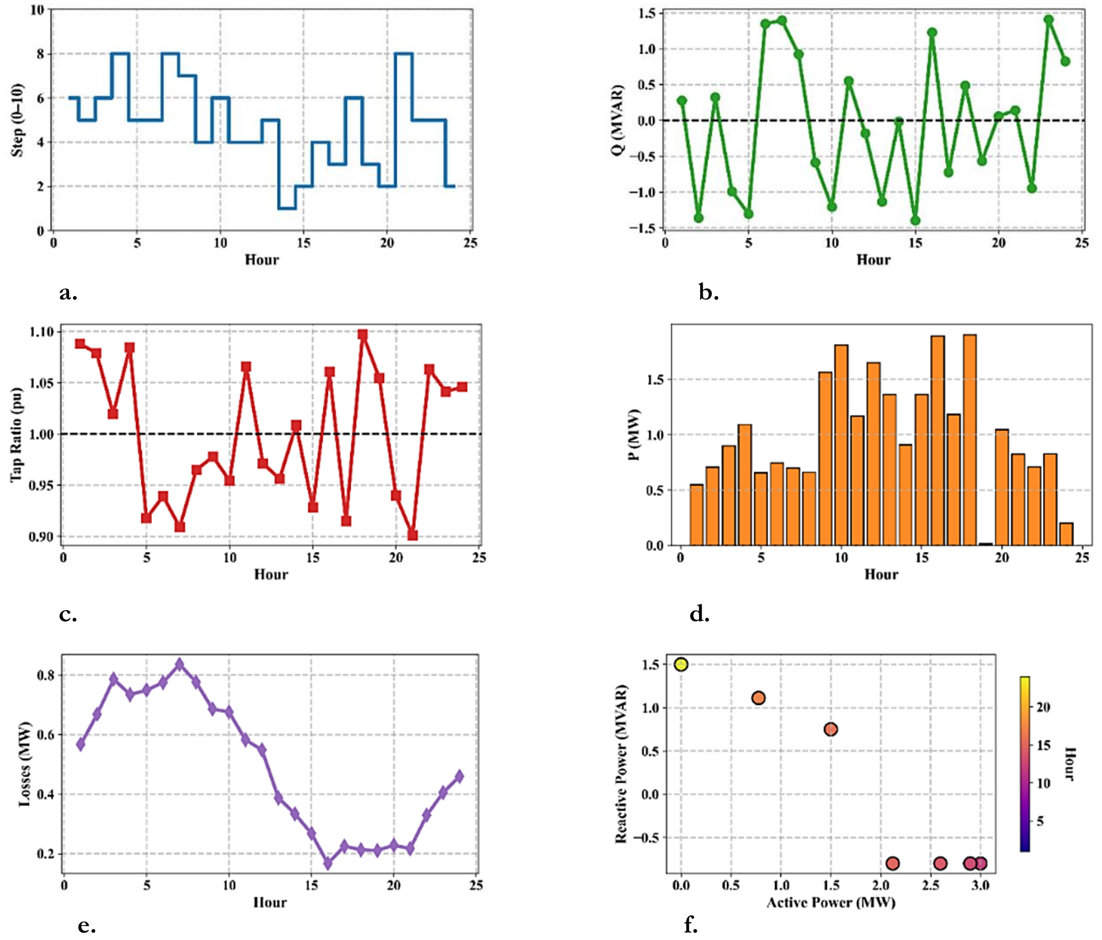


Fig. 7. Voltage profile of IEEE 33-bus system under proposed DORPC.



a.

b.

c.

d.

e.

f.

Fig. 8. Evolution of decision variables in IEEE 33 bus system; a. capacitor steps, b. DG reactive power, c. tap changer position, d. PEV charging power, e. system losses, f. PEV reactive power output.

Fig. 9 illustrates the total voltage deviations across the distribution networks obtained using the proposed holonic-based strategy. The results indicate that the holonic DORPC approach achieves voltage deviation performance nearly identical to that of the centralized method, confirming its capability to maintain system voltage within acceptable limits. As discussed previously, the reduction in voltage deviations is primarily facilitated by the holonic architecture, which enables efficient coordination with minimal computational overhead. Furthermore, the proposed strategy demonstrates substantial improvements over conventional ICS-based methods, highlighting the benefits of distributed decision-making and local resource optimization.

From the perspective of active power losses, it is critical to evaluate the performance of the proposed strategy relative to centralized and ICS approaches. *Fig. 10* presents the active power losses observed under various DORPC strategies within the distribution systems. The holonic-based method consistently exhibits superior performance in minimizing active power losses compared to the ICS model. This indicates that the proposed framework not only effectively manages voltage profiles but also optimizes reactive power flows to reduce overall system losses.

Overall, the results demonstrate that the holonic DORPC framework achieves both voltage stability and active power loss reduction while requiring fewer control actions. By leveraging local and neighboring resources through negotiation, the framework ensures efficient utilization of distributed reactive power assets, enhancing the overall operational efficiency and robustness of smart grids.

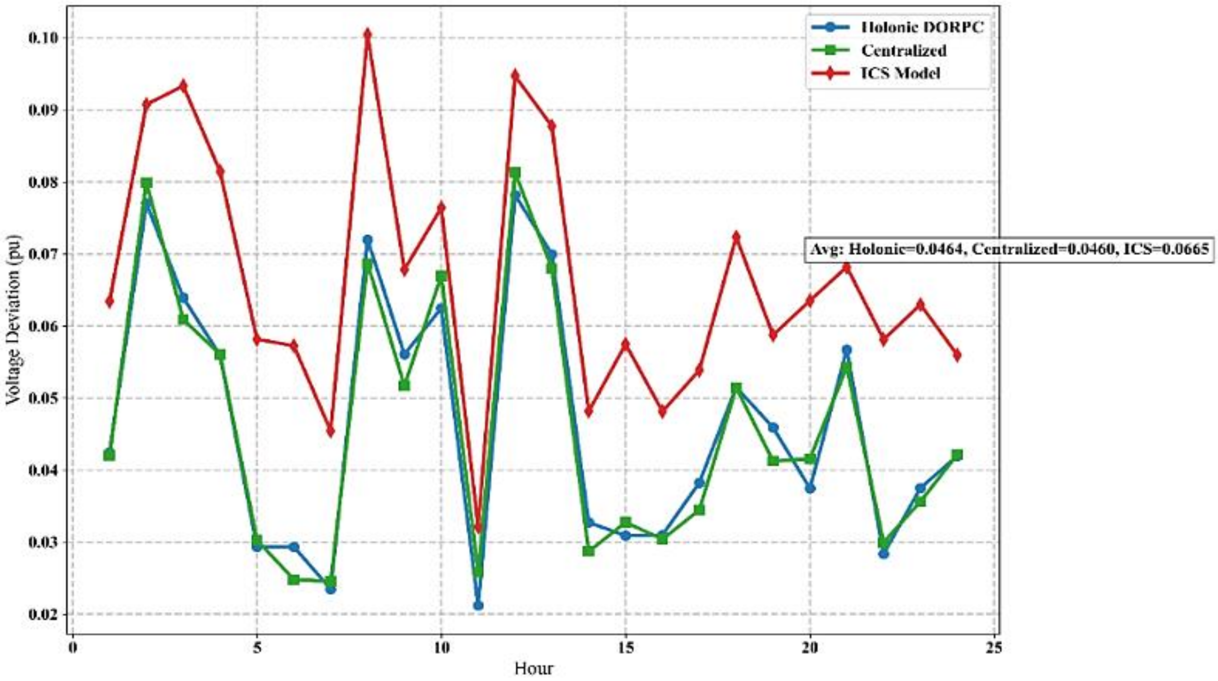


Fig. 9. Total voltage deviations in distribution networks.

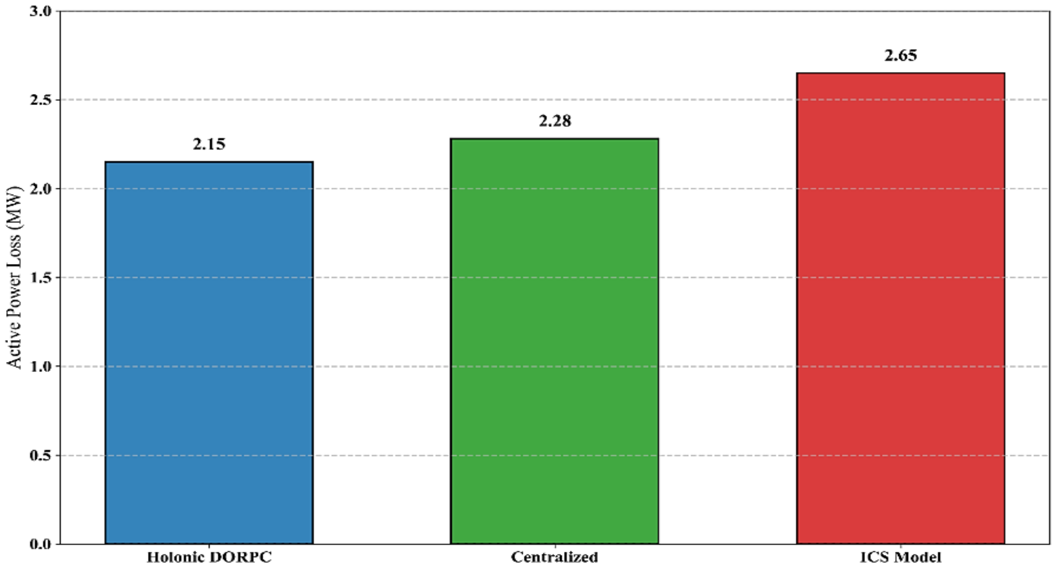


Fig. 10. Active power losses under different DORPC strategies.

9 | Communication Performance and Fault Tolerance Analysis

Given the multi-entity nature of power systems and their communication capabilities, communication performance is a critical metric in smart grids [16]. For the proposed holonic structure, if each input entity (i.e., holon) generates a data traffic rate of $\lambda_1, \lambda_2, \dots, \lambda_{EN}$, the total OAT is defined as

$$OAT = \sum_{i=1}^{EN} \lambda_i.$$

In traditional centralized control structures, OAT becomes significantly large due to the aggregation of multiple inputs. In this study, the communication data traffic between holons is computed using the JADE platform, with results presented in *Fig. 11*. In the figure, bars correspond to the total traffic (left vertical axis), while lines represent the normalized load (right vertical axis). The centralized architecture exhibits the highest traffic load, reflecting the need for all inputs to communicate with a central supervisory entity.

In contrast, the holonic structure leverages localized data exchange, transmitting only a limited subset of information to higher-level holons under exceptional conditions. Unlike the ICS framework, where all requests and commands are routed through the EMS, the decentralized holonic approach reduces redundant communication and dynamically adapts traffic patterns to align with network load profiles. Consequently, the proposed strategy minimizes bandwidth usage and enhances communication efficiency.

Fault tolerance is another critical consideration in control system design. In this study, the fault tolerance index defined in [17] is adopted to quantify system robustness. The results, shown in *Fig. 12*, indicate that the centralized structure has very low fault tolerance, as a single failure at the supervisory node can propagate system-wide outages.

Conversely, the holonic framework exhibits high fault tolerance due to its hierarchical and decentralized design. Even if a higher-level holon fails, its sub-holons can autonomously manage local operations. Additionally, sub-holons can be dynamically reassigned to neighboring or super-holons, ensuring continuity of control and mitigating the impact of failures. This adaptive self-reconfiguration underpins the robustness of the holonic architecture, demonstrating its superiority over centralized and conventional ICS approaches in both communication efficiency and fault resilience.

Fault tolerance is a critical design factor in control structures. In this study, the metric defined in [17] is adopted to model this characteristic. *Fig. 12* presents the computed fault tolerance index for the simulated structures. As shown, the centralized structure has very low fault tolerance. This reflects a system where all inputs are managed by a supervisory entity, and a single failure can lead to system-wide outage.

In contrast, in the holonic structure, even if a higher-level holon fails, lower-level holons can autonomously manage their operations. This low fault tolerance value (in a positive sense) stems from the dynamic adaptability of the holonic framework. Specifically, if a holon at a certain level fails, its sub-holons can be integrated into neighboring or super-holons, thereby increasing overall system fault tolerance

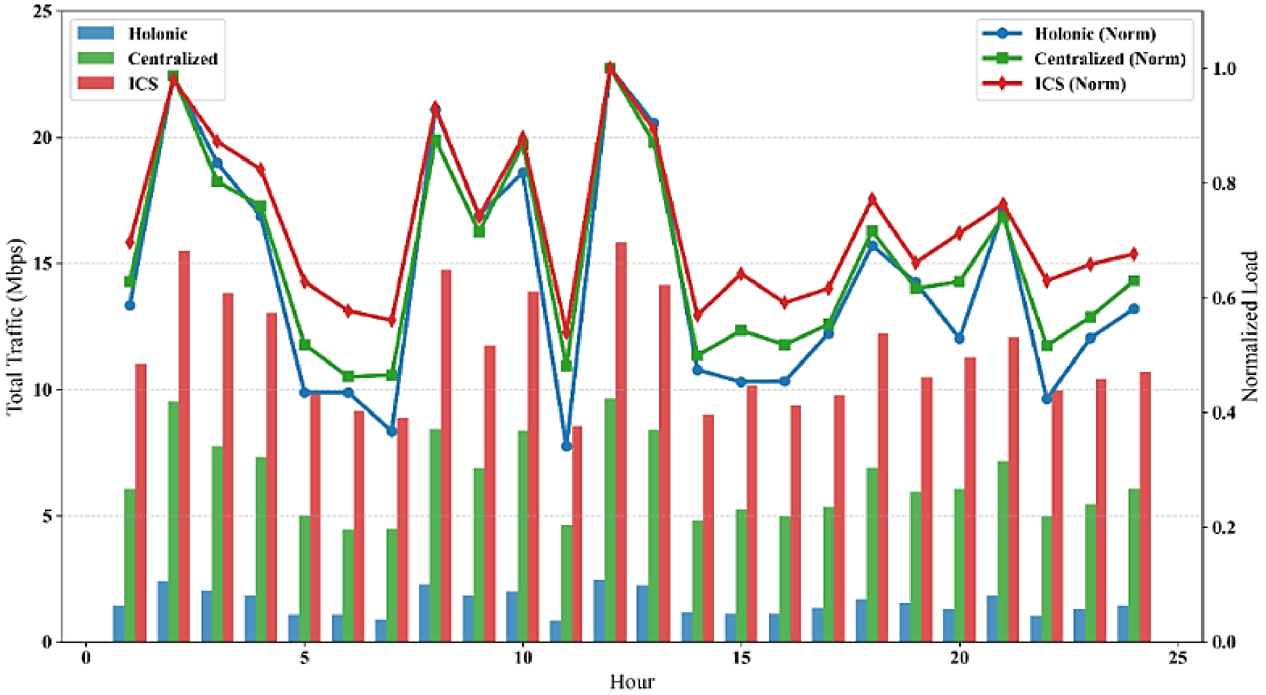


Fig. 11. Communication data traffic load (JADE platform).

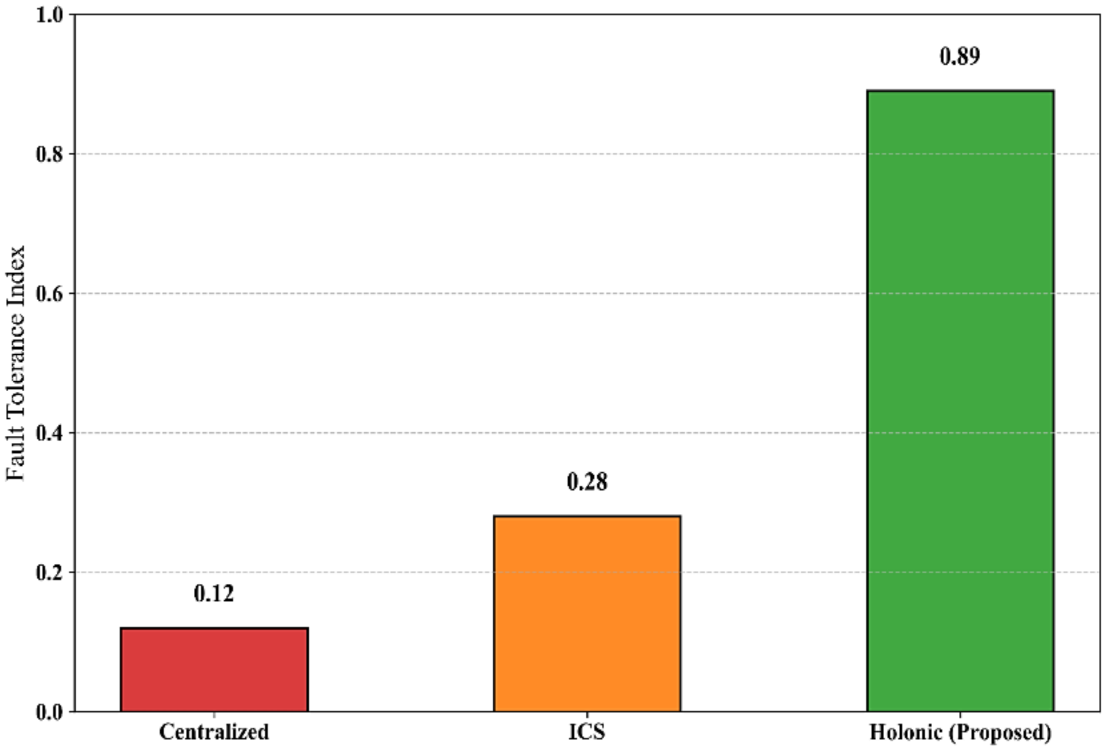


Fig. 12. Fault tolerance index comparison.

10 | Conclusion

To overcome the limitations of traditional centralized control approaches, this paper proposes a novel decentralized framework for DORPC based on a holonic architecture. The framework leverages self-organizing and self-publishing holons, which can simultaneously interact with peer holons while participating in higher-level super-holons, thereby enabling hierarchical yet collaborative operation.

By fully exploiting the inherent logic of the holonic structure, the proposed method maximizes the utilization of available reactive power resources while ensuring compliance with network security constraints. The effectiveness of the framework is rigorously validated through a comprehensive case study involving a transmission system interconnected with four distribution networks. Simulation results demonstrate that the proposed holonic-based DORPC strategy is highly compatible with the dynamic nature of smart grids, outperforming conventional methods in terms of reduced control actions and enhanced computational efficiency.

A notable advantage of the proposed approach is the reduction in decision-making latency, which directly contributes to improved system stability. Moreover, the holonic architecture achieves significant bandwidth savings in communication infrastructure, as most control decisions are made locally and data exchange with higher-level holons occurs only when necessary. The fault tolerance of the system is also markedly enhanced due to the dynamic adaptability of holons, which allows local autonomy and reconfiguration in response to component failures.

In summary, the holonic-based DORPC framework represents a scalable, resilient, and efficient solution for modern smart grids. It provides a practical pathway for implementing next-generation decentralized EMSs, capable of handling the complexities of distributed resources, variable loads, and renewable integration while maintaining robust system operation.

Author Contributions

Mahdi Ahmadzadeh proposed the core holonic-based framework and was responsible for system modeling, algorithm design, and simulation studies. Ali Bahadori contributed to the development of the decentralized control structure, implementation of the optimization process, and performance evaluation. Ramin Fazeli assisted in comparative analysis, validation of results, and refinement of the technical content. All authors contributed to manuscript preparation and approved the final version.

Acknowledgments

The authors acknowledge the valuable technical feedback received during the evaluation process, which helped enhance the robustness of the proposed framework and the clarity of its presentation. The editorial coordination that facilitated a thorough and constructive review process is also appreciated.

Funding

This work was carried out without the support of any external funding agencies and was completed through the independent efforts of the authors.

Data Availability

The findings of this study are derived from simulation-based analyses conducted on modeled power system scenarios. The simulation settings and relevant outputs can be shared with interested researchers upon reasonable request.

Conflicts of Interest

The authors declare that there are no competing interests related to this research.

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