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Original Paper

Research on the Architecture of Heliostat Field Control Systems for Solar Power Towers

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Abstract

With the development of solar power tower technology towards large-scale and high-efficiency, the selection of the network architecture for the heliostat field control system has become a critical factor affecting the overall performance of power plants. This paper systematically analyzes the technical characteristics, performance, and application scenarios of three mainstream control architectures: centralized, distributed, and hybrid. Comparative studies show that the centralized architecture is suitable for small to medium-sized demonstration projects, the distributed architecture shows advantages in ultra-large-scale power plants, and the hybrid architecture has become the mainstream choice for current commercial power plants due to its balanced performance. This paper further proposes a four-dimensional selection framework based on power plant scale, terrain conditions, investment strategy, and technical capability. Combined with emerging technology trends, it points out that cloud-edge-device collaboration, intelligent algorithm integration, and standardized design will become the core features of the next-generation architecture.

Keywords

Solar Power Tower, Heliostat Field Control, Network Architecture, Distributed Control, Hybrid Architecture

1. Introduction

Solar power tower technology achieves efficient solar-thermal conversion by concentrating solar radiation from a large-scale heliostat field onto a central receiver, making it one of the most promising renewable energy technologies today. As the “nerve center” of the power plant, the performance of the heliostat field control system directly impacts optical efficiency, operational safety, and economic viability. With the increase in single-plant capacity from the 10 MW scale to over 100 MW and the number of heliostats growing from hundreds to tens of thousands, the network architecture of control systems has undergone profound evolution.

Early solar power tower plants commonly adopted a centralized control architecture, which was simple in design but limited in scalability. With the development of distributed computing and communication technologies, distributed control architectures emerged, significantly improving system reliability and scalability. In recent years, hybrid architectures that combine the advantages of both have gradually become mainstream in the industry and have been successfully applied in several hundred-megawatt commercial projects. This paper aims to reveal the inherent characteristics, applicable boundaries, and development trends of different architectures through systematic comparative analysis, providing a theoretical basis for power plant design and optimization.

2. Centralized Control Architecture: Limitations and Value of Traditional Solutions

2.1 Architectural Principles and Technical Characteristics

The centralized control architecture adopts a classic master-slave structure, where control commands for all heliostats are uniformly calculated and issued by a central control server. This architecture typically employs a star network topology, with each heliostat connected to the central node via an independent communication link. The central server handles all core algorithms, including solar position calculation, focal point optimization, occlusion analysis, and safety monitoring, while field controllers only perform simple command reception and status feedback.

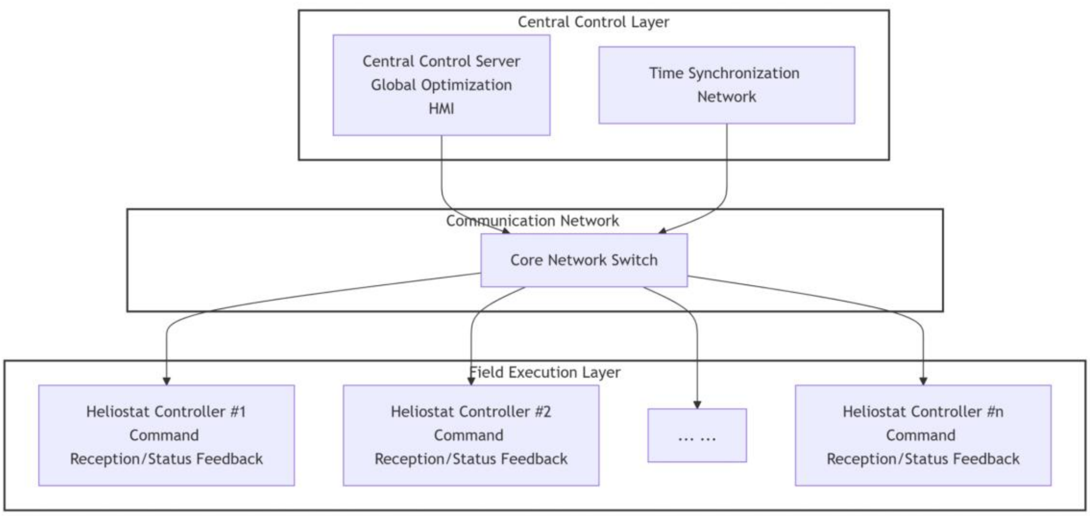

Figure 1. Centralized Control Network Architecture Diagram

This architecture features a typical star topology. The central control server acts as the sole decision-making core, communicating directly with all heliostat controllers in a "one-to-many" manner via the core network switch. Heliostat controllers have simplified functionality, responsible only for command execution and status reporting. The time synchronization network provides a unified clock reference for the entire field.

2.2 Advantages and Applicable Scenarios

The greatest advantage of the centralized architecture lies in the uniformity of control logic and the convenience of global optimization. Since all calculations are concentrated in a single node, coordinated scheduling of the entire heliostat field can be easily achieved, avoiding global efficiency loss due to local optimization. Furthermore, this architecture has lower initial investment costs and relatively simple maintenance and upgrades, making it particularly suitable for the following scenarios:

1) Small to medium-sized demonstration power plants (number of heliostats < 500)
2) Technology validation platforms: Algorithm development and testing phases
3) Capital-constrained projects: Tight initial investment budgets

2.3 Limitations Analysis

However, the fundamental flaw of the centralized architecture lies in its scalability bottleneck. As the number of heliostats increases, the computational load on the central server grows geometrically, and communication delays increase significantly. Research indicates that when the number of heliostats exceeds 1,000, the control cycle may extend from milliseconds to hundreds of milliseconds, severely affecting tracking accuracy. Additionally, the risk of single-point failure is a critical weakness of the centralized architecture—failure of the central server can lead to a complete field shutdown, resulting in significant power generation losses.

3. Distributed Control Architecture: A Breakthrough Direction for Technological Innovation

3.1 Architectural Philosophy and Technical Implementation

The distributed control architecture decentralizes computing power to edge nodes, with each heliostat or heliostat group equipped with an intelligent controller capable of independent decision-making and execution. These controllers form a peer-to-peer or hierarchical communication network via field buses (e.g., CAN, PROFIBUS) or industrial Ethernet (e.g., EtherCAT, PROFINET), enabling local coordinated control.

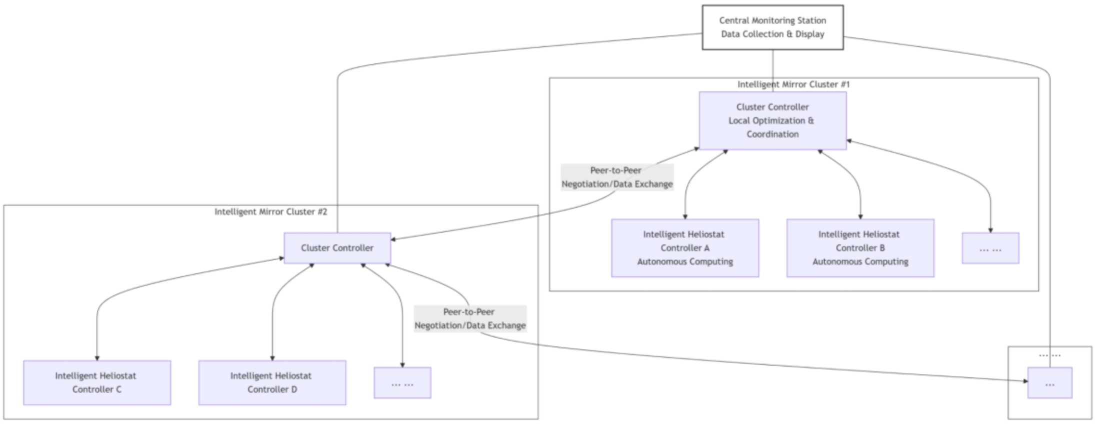

Figure 2. Distributed Control Network Architecture Diagram

This architecture features a hierarchical peer-to-peer network topology. The system is divided into multiple intelligent mirror clusters. Controllers within each cluster possess autonomous computing capabilities and coordinate locally via the cluster controller. The central monitoring station is only responsible for data collection and display and does not intervene in real-time control. Different mirror clusters can perform peer-to-peer negotiation and data exchange over the network, achieving truly distributed decision-making.

3.2 Core Advantages

The core advantages of the distributed architecture are reflected in three aspects:

System Reliability: The “decentralized” design ensures that any single-point failure only affects a local area, and the system retains degraded operational capability. Studies show that, assuming the same hardware reliability, the system availability of a distributed architecture can be 15%-20% higher than that of a centralized architecture.

Scalability Flexibility: The modular design simplifies power plant expansion. Adding new heliostat groups only requires connection to the local network, without modifying the central system. This characteristic makes distributed architecture particularly suitable for large-scale power plants constructed in phases.

Real-time Performance: Local control loop delays can be controlled within 10 milliseconds, maintaining excellent tracking performance even in systems with tens of thousands of heliostats.

3.3 Implementation Challenges and Solutions

Implementing a distributed architecture faces challenges in coordinated control and consistency maintenance. To address these issues, the industry has developed various distributed coordination algorithms:

1) Consensus Algorithms: Achieving state consistency based on Paxos or Raft algorithms.
2) Distributed Optimization: Using algorithms like ADMM (Alternating Direction Method of Multipliers) to decompose global optimization.

3) Event-Driven Communication: Reducing unnecessary network communication to lower bandwidth requirements.

Despite technological advancements, the high cost and maintenance complexity of distributed architectures remain major factors limiting their widespread adoption.

4. Hybrid Control Architecture: Current Practice of the Balanced Approach

4.1 Three-Layer Architecture Design Philosophy

The hybrid control architecture creatively integrates the advantages of both centralized and distributed approaches, forming a three-tier structure: “Central Coordination - Regional Control - Terminal Execution.”

Top Layer (Central Coordination Layer): Responsible for long-term strategy formulation, performance analysis, and plant-wide scheduling, with a control cycle ranging from minutes to hours.

Middle Layer (Regional Control Layer): Each regional controller manages 200-500 heliostats, achieving local optimization and rapid response, with a control cycle on the order of seconds.

Bottom Layer (Terminal Execution Layer): Individual heliostat controllers handle millisecond-level precise positioning and fault protection.

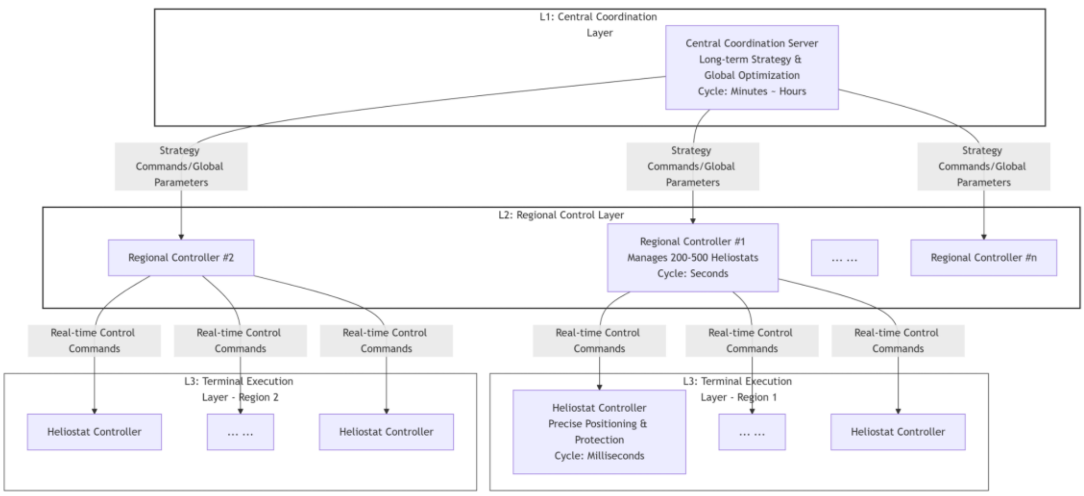

Figure 3. Hybrid (Three-Layer) Control Network Architecture Diagram

This architecture clearly illustrates the three-tier hierarchical structure of “Central Coordination - Regional Control - Terminal Execution.” The central layer is responsible for non-real-time global optimization; the regional layer acts as an intermediate hub, decomposing global strategies into local real-time commands; and the terminal layer achieves high-precision closed-loop control. Each layer has different control cycles and communication requirements, achieving the optimal balance of performance, reliability, and cost.

4.2 Typical Application Case Analysis

Taking the Noor III 150 MW solar power tower plant in Morocco as an example, this project is a global benchmark for the application of advanced hybrid control architectures. The plant concentrates solar energy through approximately 7,400 heliostats. Its control system typically adopts a hierarchical "central coordination - regional control - terminal execution" architecture. In such an architecture, the central optimization layer is responsible for plant-wide scheduling strategies on a minute-to-hour timescale, the regional control layer achieves second-level local collaborative optimization, and the terminal execution layer performs millisecond-level high-precision positioning and closed-loop control. This hierarchical and collaborative design is widely recognized as one of the key factors enabling the plant's high-performance operation. Industry assessments indicate that its heliostat field system achieves excellent efficiency levels, demonstrating the successful application of hybrid architecture in large-scale commercial projects (based on IEA SolarPACES project overview and industry practice analysis).

4.3 Techno-Economic Analysis

The hybrid architecture achieves a good balance between technical performance and economic cost. Compared to a purely distributed architecture, its investment cost can be reduced by 20%-30%, while system availability remains above 99.5%. This cost-performance advantage makes it the mainstream choice for current commercial power plants in the 50-200 MW range.

5. Multi-Dimensional Comprehensive Comparison and Selection Framework

5.1 Quantitative Comparison of Key Technical Indicators

Table 1. Quantitative Comparison of Key Technical Indicators

Evaluation Dimension	Centralized Architecture	Distributed Architecture	Hybrid Architecture
Control Accuracy (mrad)	1.5-2.5 (degrades at large scale)	0.8-1.2	1.0-1.5
System Availability (%)	98.0-99.0	99.5-99.8	99.2-99.6
Expansion Cost ($/heliostat)	High (requires central system upgrade)	Low (modular addition)	Medium
Communication Bandwidth Req. (Mbps)	100-500 (entire field)	10-50 (local network)	Hierarchical design, backbone 50-100
Typical Response Delay (ms)	50-200	5-20	10-50
Applicable Scale (# of heliostats)	< 500	All scales, >3000 shows clear advantage	500 - 3000

Note. The data in this table are synthesized from industry literature, technical white papers, and analysis of typical project cases. They represent typical ranges, and actual values may vary depending on specific project design, equipment selection, and environmental conditions.

5.2 Four-Dimensional Selection Decision Model

Based on retrospective analysis of several built projects, this paper proposes the following selection decision framework:

Dimension 1: Scale Factor

- <500 heliostats: Centralized architecture is most economical.
- 500-3000 heliostats: Hybrid architecture offers the highest comprehensive benefit.
- 3000 heliostats: Distributed or advanced hybrid architecture is more reliable.

Dimension 2: Terrain Conditions

- Flat terrain: Wired communication solutions have controllable costs.
- Complex terrain: Wireless communication + distributed control shows clear advantages.

Dimension 3: Investment Strategy

- Need for quick returns: A simplified hybrid architecture can be adopted initially.
- Long-term operation orientation: Should invest in scalable advanced architecture.

Dimension 4: Technical Capability

- Experienced team: Can consider customized solutions.
- Standardization priority: Choose proven commercial solutions.

6. Future Development Trends and Technological Outlook

6.1 Integration of Intelligent Algorithms

Artificial intelligence and machine learning technologies are being deeply integrated into control system architectures. Digital twin technology can create virtual replicas of heliostat fields, enabling predictive maintenance and optimized control. Reinforcement learning algorithms can adaptively adjust control strategies to cope with dynamic disturbances such as cloud cover and wind loads.

6.2 Evolution of Communication Technologies

The development of 5G and industrial wireless networks provides new possibilities for heliostat field control. Ultra-Reliable Low Latency Communication (URLLC) features can support wireless closed-loop control, significantly reducing wiring costs and maintenance difficulty. Satellite-terrestrial integrated communication and other technologies provide alternative solutions for power plants in extremely remote areas.

6.3 Standardization Progress

The IEC 62862 series of standards developed by the International Electrotechnical Commission (IEC) is promoting the standardization of control system architectures. In the future, open architectures and interoperability will become basic industry requirements, facilitating seamless integration of equipment from different manufacturers.

6.4 Deepening of Cloud-Edge-Device Collaboration

The next-generation architecture will further clarify the functional division of each level: the cloud will be responsible for big data analysis and long-term optimization, edge computing nodes will handle real-time coordinated control, and terminal devices will focus on precise execution. This collaborative model can achieve the perfect combination of global optimization and local rapid response.

7. Conclusion

The selection of a network architecture for the heliostat field control system in solar power tower plants is a complex multi-objective optimization problem that requires comprehensive consideration of technical, economic, and operational factors. This study draws the following conclusions through systematic analysis:

1) The three mainstream architectures each have their applicable scenarios; there is no "one-size-fits-all" optimal solution. The choice should be customized based on specific project conditions. The centralized architecture retains value in small projects and technology validation due to its simplicity and economy; the distributed architecture represents the technological frontier and is the inevitable direction for ultra-large-scale power plants; and the hybrid architecture demonstrates the best balance under current techno-economic conditions, making it the preferred choice for commercial power plants above 50 MW.
2) The four-dimensional selection decision model (scale, terrain, investment, technical capability) proposed in this paper provides a systematic decision-making tool for project architecture selection, helping to avoid one-sidedness in technical solutions.
3) As power plant scales expand and technology advances, the concept of distributed control will gain more traction. Future successful control system architectures should possess the following characteristics: a layered and decoupled design philosophy, open and compatible interface standards, support for adaptive intelligent algorithms, and lifecycle cost optimization capability. Intelligence, wireless technology, and standardization will become the main directions of architectural evolution.

It is recommended that new projects adopt the design principle of "moderately advanced, flexibly scalable." While meeting current needs, space should be reserved for technological upgrades and capacity expansion. Particularly for large-scale power plants planned for phased construction, initially choosing a transitional architecture that can be smoothly upgraded to hybrid or distributed systems is a key strategy to ensure the plant maintains technological competitiveness and economic feasibility throughout its lifecycle.

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