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A COMPARATIVE ANALYSIS OF MICROGRID CONTROL STRATEGIES FOR INDUSTRIAL AND COMMUNITY ENERGY SYSTEMS

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ABSTRACT

INTRODUCTION: Microgrids have emerged as a key enabler of modern decentralized energy systems, providing resilience, flexibility, and enhanced integration of renewable energy resources. However, the performance and stability of microgrids critically depend on the choice of control strategy. Industrial microgrids typically require fast dynamic response, high reliability, and tight power-quality performance, whereas community microgrids prioritize affordability, renewable integration, and resilience against outages. The diversity of applications creates a need for a comprehensive comparative analysis of available microgrid control strategies including droop control, virtual synchronous machine (VSM), model predictive control (MPC), multi-agent control, robust and adaptive controllers, and hierarchical architectures.

METHOD: This article presents a rigorous comparative analysis of microgrid control strategies for industrial and community-scale applications. The study includes mathematical modelling of inverter-based distributed energy resources (DERs), stability analysis under varying load and renewable penetration, evaluation of power-quality metrics, and assessment of resilience under disturbances. A unified simulation framework is developed, encompassing primary, secondary, and tertiary control layers for grid-connected and islanded modes.

FINDINGS: The results show that droop control remains effective for rural and community microgrids where cost and simplicity are priorities, but exhibits reduced precision under high renewable variability. Virtual synchronous machine control improves transient stability and inertia support, making it suitable for industrial microgrids with sensitive loads. Model predictive control delivers superior optimization performance and fast response but requires high computational resources. Multi-agent control enhances resilience and autonomy, making it a viable strategy for community microgrids with distributed ownership. A hybrid control framework is proposed that combines VSM-based inertia with secondary adaptive control and tertiary MPC-based optimization.

CONCLUSION AND RECOMMENDATION: The research contributes a detailed performance comparison across eight metrics: voltage stability, frequency regulation, power quality, dynamic response, computational complexity, renewable accommodation, resilience, and cost. The thesis concludes by recommending optimal control strategies for different microgrid categories and operational needs, and highlights areas for future research including AI-enhanced predictive controllers, cyber-resilient frameworks, and scalable multi-agent architectures.

Keywords:
Microgrids; Community microgrids; Droop control; Hierarchical control; Distributed control; Model predictive control; Stability analysis;

INTRODUCTION

Distributed generators (DG) can effectively improve the utilization efficiency of clean energy, accelerate the energy transformation to be more sustainable, and reduce generation costs (Mohammadi, et al., 2022). Strategically placing distributed generators (DGs) within the power systems can yield several benefits, such as reducing peak operating costs and power losses, improving voltage distribution, meeting load requirements, and enhancing overall system reliability and integrity (Xu, et al., 2022).

Microgrids localized energy systems that integrate distributed energy resources (DERs), storage, and loads play a crucial role in enhancing resiliency, increasing renewable penetration, and improving power quality (Li et al., 2023). The control strategy adopted in a microgrid strongly influences its stability, economic performance, and capacity to

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operate both in grid-connected and islanded modes. For industrial microgrids, reliability and fast response are critical, while in community microgrids, flexibility, cost optimization, and adaptability to variable renewable generation are often more important.

Traditional hierarchical control architectures (primary/secondary/tertiary) remain widespread because of their maturity and robustness, but advanced methods such as Model Predictive Control (MPC) and Reinforcement Learning (RL) are gaining traction due to their optimization capabilities and adaptability (Li et al., 2023; Chaturvedi et al., 2023).

A community microgrid is an autonomous energy network that incorporates power generation, energy storage, and energy management components to serve the needs of a nearby community (Cornélusse, et al., 2019). Community microgrid is a collection of distributed energy resources (DERs) and consumers in a designated electrical region that may autonomously disconnect from and reconnect to the main grid (Eklund, et al., 2023). A community microgrid's primary goal is to reduce a community's reliance on the main grid while supplying a dependable and sustainable energy supply. Depending on the availability of power from the main grid, a community microgrid can operate in either an isolated mode or a mode that is connected to the main grid. When in island mode, the microgrid runs independently from the main grid and supplies all of the energy it needs from its own local resources (Eklund, et al., 2023). The microgrid can draw power from the main grid when necessary while it is operating in grid-connected mode. Community microgrids can include various types of power generation resources such as solar panels, wind turbines, biomass, vibration energy and diesel generators (Li, et al., 2018). Where, one dependable way to help sensor nodes in distant areas that are experiencing an energy shortage is using vibration energy sources. The society and upcoming researchers are fortunate to have access to vibration energy harvesting (Halim, et al., 2022). Energy storage systems, such as batteries and flywheels, are also incorporated to store excess energy and provide backup power during outages.

Advanced control strategies, such as optimal power flow and economic dispatch, can be used to optimize the operation of the community microgrid, ensuring that it operates in the most efficient and cost-effective manner. The use of community microgrids can improve the reliability and sustainability of the energy supply for the community, while also reducing dependence on the main grid (Mishu at al., 2020). A comparative study on various control strategies for community micro-grid is an analysis that aims to compare and evaluate different techniques for controlling the operations of a micro-grid in a community setting (Saleh,, et al., 2022). With the increasing use of micro-grids for decentralizing the energy supply, it is important to determine the best control strategy for optimizing the performance of these systems.

The primary aim of this comparative study is to assess various control strategies for community micro-grids, including islanded mode control, grid-connected mode control, hybrid mode control, and advanced control strategies that incorporate optimization techniques like optimal power flow and economic dispatch. The comparison is made based on factors such as stability, reliability, efficiency, cost- effectiveness, and resilience.

STATEMENT OF THE PROBLEM

Choosing the right control strategy for a microgrid requires a careful balance of multiple, sometimes competing, priorities. In industrial microgrids**,** stability, reliability, and operational simplicity are often paramount, because these systems typically power sensitive equipment or continuous-process operations where even small disturbances in voltage or frequency can lead to significant losses. Classical droop-based control paired with hierarchical secondary and tertiary control layers is especially attractive in these contexts due to its robustness, minimal communication needs, and proven field performance (Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023).

On the other hand, community microgrids usually face high variability in both load and generation, particularly when there is significant penetration of renewables and distributed storage. In these settings, the ability to adapt and optimize under uncertainty becomes more important than sheer robustness. Advanced strategies like Model Predictive Control (MPC) allow systems to predict future behavior, account for constraints, and optimally allocate energy resources (Energies, 2023). However, MPC implementations require accurate forecasts, higher computational capacity, and reliable communication infrastructure (Energies, 2023).

Meanwhile, Reinforcement Learning (RL) based control offers a data-driven, adaptive framework that learns optimal policies in the face of stochastic dynamics and real-time disturbances. RL has shown promise for microgrid energy

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management and frequency regulation, though safety, convergence speed, and real-world deployment remain challenging (Yao, Zhao, Forshaw & Song, 2023).

Despite these advances, there is still limited direct comparative evidence evaluating droop/hierarchical control against MPC or RL under standardized conditions across different microgrid types. Most studies examine these approaches in isolation or focus on specific metrics (e.g., voltage regulation, cost) rather than offering a comprehensive analysis across application contexts (Almihat & Munda, 2023; Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023).

This project addresses that gap by conducting systematic comparative experiments using two representative microgrid models one industrial and one community. The microgrids will be deployed in simulation and exposed to identical disturbance scenarios (including renewable intermittency, load fluctuations, fault conditions, and islanding) to ensure comparability. Four control strategies will be benchmarked: traditional droop/hierarchical control, MPC-based control, RL-based control, and a hybrid architecture that combines all three.

Their performance will be evaluated using a comprehensive set of techno-economic metrics: stability (frequency and voltage deviations), power quality (e.g., total harmonic distortion), resilience under fault conditions, control-related cost (both capital and operational), computational complexity, and reliance on communication infrastructure. The project further applies Multi-Criteria Decision Analysis (MCDA)**,** weighting each metric according to stakeholder priorities (e.g., industrial operators may value reliability more, while community stakeholders may emphasize cost and renewable utilization).

By integrating simulation results with stakeholder-informed decision analysis, the study aims to provide actionable guidance on which control strategies are most appropriate for different microgrid applications. This evidence-based approach promises to bridge the gap between theoretical advances (such as MPC and RL) and practical implementation in real-world industrial and community microgrids.

RESEARCH QUESTIONS

1. How do industrial and community microgrids differ in terms of load characteristics, reliability requirements, renewable energy penetration, demand patterns, and regulatory constraints?
2. How can representative simulation models for industrial and community microgrids be designed, integrating realistic load profiles, generation assets, storage systems, and grid-interaction settings?
3. How do different control strategies affect key performance metrics such as frequency and voltage stability, energy efficiency, reliability indices, power quality, dispatch accuracy, computational complexity, and resilience to disturbances?
4. Which strategies are most suitable for both industrial and community microgrids prioritizing flexibility, affordability, and effective renewable integration?
5. What are the strengths, limitations, and practical challenges associated with each control strategy in real-world deployment?

RESEARCH OBJECTIVES

General Objectives:

The General objective of this study is to analyse, compare, and evaluate microgrid control strategies for industrial and community energy systems**,** focusing on their performance, stability, reliability, cost-effectiveness, and suitability under varying operational and environmental conditions.

Specific Objectives:

1. To classify industrial and community microgrid systems based on their load characteristics, reliability requirements, renewable energy penetration levels, demand patterns, and regulatory constraints.
2. To design simulation models for industrial and community microgrids in a suitable environment such as MATLAB/Simulink, DIgSILENT Power Factory, or OpenDSS, integrating representative load profiles, generation assets, storage systems, and grid-interaction settings.
3. To evaluate each control strategy based on key performance metrics, including frequency and voltage stability, energy efficiency, reliability indices, power quality, optimal dispatch accuracy, computational complexity, and resilience to disturbances.

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4. To analyse and compare the suitability of each control strategy for industrial microgrids (which require high reliability, robustness, and low latency) and community microgrids (which require flexibility, affordability, and effective renewable integration).
5. To identify the strengths, limitations, and practical implementation challenges associated with each control approach in real-world settings, considering issues such as communication requirements, scalability, cyber-security, and interoperability..

THEORETICAL FRAMEWORK

Microgrids are defined by the IEC as: “a group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode.” The importance of the microgrid lies in providing reliability and resiliency to the connected loads within their boundaries and possibly providing auxiliary services to the primary grid in some cases. In addition, Microgrid aims to provide continuous service to loads following natural disasters and faults in the primary grid, especially when the grid has undergone a blackout.

1. Systems Theory

Systems Theory provides a holistic conceptual framework for understanding microgrids as interconnected, adaptive systems composed of multiple interacting components that work together to maintain stable and efficient operation. In the context of microgrid control and energy management, Systems Theory emphasizes that no component whether it is a solar PV unit, battery storage system, diesel generator, smart inverter, or communication link functions in isolation. Instead, each element influences and is influenced by the operational behavior of all other components through feedback loops, control decisions, and external disturbances.

A microgrid is inherently a cyber-physical system, meaning it incorporates both physical electrical infrastructure and cyber layers such as communication networks and control algorithms. Systems Theory helps explain how these layers integrate to achieve common goals such as voltage stability, frequency regulation, optimal power flow, and economic dispatch. For example, solar generation may fluctuate due to irradiance changes, which immediately affects the power balance. Battery storage systems may then inject or absorb power based on control signals. Simultaneously, the secondary control layer may adjust set points to correct deviations, while tertiary control optimizes power exchange with the main grid. Systems Theory clarifies these multi-layer interactions by providing a structured way of understanding subsystems, boundaries, inputs, outputs, and internal processes.

Feedback mechanisms are central to Systems Theory and highly relevant to microgrid control. Through continuous monitoring of voltage, frequency, and state-of-charge (SOC), control systems generate real-time corrective actions, ensuring the system remains within safe operating limits. When disturbances occur such as a sudden load increase, a generator outage, or communication delay Systems Theory describes how these disturbances propagate through the system. This understanding supports the design of resilient control strategies that mitigate cascading failures.

Systems Theory also emphasizes emergence, the phenomenon where collective system behavior cannot be predicted solely from individual components. In microgrids, complex emergent behaviors arise when distributed resources use droop control, adaptive strategies, or multi-agent coordination. For instance, decentralized controllers may autonomously adjust power outputs, leading to emergent stability patterns even without centralized supervision. This theoretical lens helps engineers anticipate system-wide behavior resulting from local control rules.

Additionally, Systems Theory highlights the importance of subsystem integration. Microgrids require coordination among energy resource management, cybersecurity, communications, and physical power flows. Integrating renewable forecasting, load prediction, and market-based control strategies further complicates the dynamics. Systems Theory supports the design of control architectures that ensure coherence across these interacting components.

In summary, Systems Theory provides an essential foundation for microgrid control research and practice. By recognizing the microgrid as a unified, interdependent system, the theory supports improved stability, resilience, and efficiency. It guides the development of hierarchical control structures, distributed control strategies, and adaptive energy management frameworks that respond effectively to the dynamic behavior of modern microgrids.

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2. Control Theory

Control Theory is one of the most fundamental theoretical foundations for microgrid operation, providing the mathematical and conceptual tools required to regulate voltage, frequency, power flow, and stability. Microgrids operate in dynamic environments with continuously changing loads, renewable fluctuations, and switching events. Control Theory enables the design of algorithms that maintain system equilibrium and ensure safe, efficient performance under these conditions.

At its core, Control Theory involves managing system outputs by manipulating inputs based on feedback or predictive models. In microgrids, the primary outputs requiring regulation include voltage magnitude, frequency, power factor, reactive power, and state-of-charge (SOC). Inputs include inverter set points, generator excitation signals, battery charge/discharge levels, and power electronics commands. Control Theory governs how these inputs are adjusted to maintain desired outputs.

Primary control in microgrids relies heavily on classical Control Theory, particularly proportional-integral (PI) controllers, droop control methods, and virtual impedance shaping. Droop control, derived from Control Theory principles, allows distributed generators to share load proportionally without requiring communication links. This decentralized strategy ensures that each inverter or generator autonomously adjusts its power contribution to maintain frequency and voltage stability. Control Theory helps determine gain values, stability margins, and dynamic responses to disturbances.

Secondary control employs advanced feedback mechanisms to restore voltage and frequency to nominal values after primary control stabilizes the immediate system response. Control Theory supports the design of centralized or distributed secondary controllers that calculate corrective set points. Techniques such as consensus control, adaptive control, and model reference control contribute to high-precision regulation and robustness against uncertainties.

Tertiary control incorporates concepts from optimal control, including linear programming, convex optimization, and cost minimization. These control structures coordinate economic dispatch, power exchange with utilities, demand response, and reserve scheduling. Model predictive control (MPC), a sophisticated form of optimal control, predicts future system states using models and solves optimization problems in real time. Control Theory frameworks guide MPC development, including objective functions, constraints, and prediction horizons.

Control Theory also provides essential tools for analyzing microgrid stability, such as Lyapunov functions, eigenvalue analysis, and system identification. With renewable energy sources introducing stochastic behavior, robust and adaptive control strategies are needed. Control Theory supports designing controllers that can withstand uncertainties such as fluctuating irradiance, communication delays, or changes in system topology.

Furthermore, Control Theory informs the development of virtual synchronous machines (VSMs), where inverters emulate the inertia and damping of synchronous generators. The mathematical models governing these systems based on classical swing equations are rooted in Control Theory.

Overall, Control Theory remains indispensable for microgrid research and implementation. It enables the design of precise, reliable, and adaptive control strategies necessary for achieving stable operation across grid-connected and islanded modes.

3. Complexity Theory

Complexity Theory offers a powerful lens for understanding microgrids, particularly as modern microgrids grow in scale, heterogeneity, and interconnectedness. A microgrid is a complex adaptive system (CAS), composed of diverse interacting components renewable energy sources, storage units, controllable loads, power electronic converters, and communication infrastructure that dynamically change in response to internal and external conditions. Complexity Theory studies how such systems exhibit emergent behavior, nonlinear dynamics, self-organization, and adaptation, all of which are directly relevant to microgrid operation.

A defining aspect of microgrids is their nonlinear responses to disturbances. For example, when solar output fluctuates, battery storage may react, loads may shift, and controllers adjust setpoints actions that collectively influence system behavior in ways not always predictable from individual elements. Complexity Theory explains how these interdependencies produce dynamic responses that cannot be understood through linear models alone. Microgrid voltage and frequency regulation often involve nonlinear differential equations and nonlinear control responses, making Complexity Theory essential.

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Microgrids also exhibit emergent behavior. For example, decentralized droop-controlled inverters autonomously adjust their power contributions without central coordination, yet together they achieve stable power sharing. Complexity Theory explains such emergent coherence resulting from simple local rules. Similarly, multi-agent systems where each agent makes autonomous decisions can achieve global optimization even without central control. Emergent dynamics become increasingly important as microgrids expand into multi-microgrid clusters or community energy networks.

Self-organization is another core concept from Complexity Theory. Microgrids continually self-organize in response to changing operating modes (grid-connected vs. islanded), load variations, faults, or economic signals. For instance, during islanding, microgrids automatically reconfigure power flows and adjust control hierarchies to maintain stability. This adaptive restructuring reflects principles of self-organization.

Adaptation is also crucial. Modern microgrids incorporate machine learning-based forecasting, demand response, and adaptive control algorithms that learn from historical data. These adaptive processes modify system behavior over time, aligning with Complexity Theory's emphasis on evolving system dynamics.

Additionally, Complexity Theory supports resilience analysis. Microgrids face uncertainties such as renewable variability, cyber threats, component faults, and communication failures. Complexity Theory helps model how disturbances propagate through interconnected components and how resilient control strategies can mitigate cascading failures.

Finally, Complexity Theory provides tools for analyzing multi-layer interactions (physical, cyber, economic), enabling comprehensive understanding of next-generation smart microgrids.

4. Energy Management Theory

Energy Management Theory provides a conceptual and analytical framework for optimizing the planning, scheduling, and operation of distributed energy resources (DERs) within microgrids. Its goal is to ensure that energy supply meets demand reliably, sustainably, and economically. The theory addresses how decisions are made regarding energy generation, storage, consumption, and exchange with the main grid.

At the core of this theory lies optimization. Microgrid operators must manage multiple, often conflicting objectives: minimizing cost, maximizing reliability, reducing emissions, extending battery life, and maintaining power quality. Energy Management Theory helps integrate these objectives into mathematical optimization frameworks such as linear programming, mixed-integer optimization, dynamic programming, or stochastic programming. These models are used in tertiary control applications for economic dispatch, scheduling of DERs, and market participation.

Forecasting is essential to Energy Management Theory. Accurate predictions of solar irradiance, wind speeds, load profiles, and energy prices inform the decision-making process. Forecasting improves optimization accuracy and reduces operational costs. The theory also considers uncertainties, designing robust and stochastic models that anticipate variability and incorporate probabilistic constraints.

Energy Management Theory includes load management and demand response. Through price signals or control commands, certain loads can be shifted or curtailed to balance supply-demand mismatches. This aligns with the theory's focus on minimizing costs while ensuring energy availability.

The theory also addresses storage management. BESS units require optimized charging and discharging schedules to prevent overuse, minimize degradation, and maintain readiness for contingencies. Advanced scheduling strategies consider SOC, cycle limits, efficiency losses, and degradation costs.

Energy Management Theory guides the design of hierarchical and distributed energy management systems (EMS), ensuring coherent decision-making across primary, secondary, and tertiary layers.

5. Socio-Technical Systems Theory

Socio-Technical Systems (STS) Theory provides a holistic lens for understanding how technological infrastructures and human factors co-evolve within energy systems. Within the microgrid context, this theory acknowledges that energy solutions do not exist in isolation they are shaped by interacting technical, social, economic, institutional, and environmental subsystems. Because industrial and community microgrids operate in fundamentally different social environments and serve distinct user groups, STS Theory is particularly useful for analyzing how control strategies, technology choices, governance models, and user behaviors influence overall performance.

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At its core, STS Theory argues that technology adoption and system performance depend not only on engineering design but also on social acceptance, organizational behavior, policy frameworks, and cultural norms. For example, a technically superior control strategy may not succeed if community members cannot understand or trust it, or if institutional arrangements do not support collaborative decision-making. Similarly, industrial microgrids may require advanced automation and high-speed supervisory control because of productivity requirements, but these solutions may be inappropriate for rural community microgrids with limited funding and technical expertise.

In industrial microgrids, the socio-technical environment is highly structured, with formal decision-making hierarchies, stable funding streams, trained personnel, and clear operational objectives such as cost reduction, reliability, and productivity. STS Theory helps illustrate how these conditions support centralized or hierarchical control strategies that optimize precision, production continuity, and energy efficiency. Human roles are specialized, operators are trained, and maintenance schedules are systematic. As a result, advanced optimization-based or model-predictive control (MPC) strategies are often feasible, as the social environment supports the high technical complexity required.

In contrast, community microgrids operate within more diverse and fluid socio-economic environments. These systems are shaped by household energy needs, local cultures, affordability constraints, seasonal consumption patterns, and varying levels of technical literacy. STS Theory helps explain why decentralized or distributed control strategies often perform better in these settings they allow local autonomy, resilience, and gradual capacity building. Community involvement is central, because user behavior such as load-shifting willingness or tariff acceptance directly affects microgrid stability and sustainability. Social dynamics such as trust, equity, and communal decision-making heavily influence system performance.

STS Theory also highlights the importance of institutional and policy factors. Industrial microgrids frequently operate under corporate policies that prioritize return on investment, regulatory compliance, and long-term asset management. Community microgrids, however, are more sensitive to national electrification policies, subsidies, donor programs, and local governance structures. For example, tariff-setting mechanisms must balance system sustainability with affordability. Failures in any social or institutional element such as poor governance or inadequate community training can cause technical failures regardless of the sophistication of the control system.

Lastly, environmental and economic subsystems also shape microgrid control strategies. Resource variability (e.g., solar availability), climate impacts, and local economic activities (e.g., farming vs. manufacturing) influence load patterns and energy priorities. STS Theory emphasizes that optimal microgrid solutions emerge only when the technical strategy is harmonized with social needs, economic realities, and institutional capacities.

Microgrid Topology

Various microgrid topologies and DER combinations have been reported in the literature. As per our survey, PV and Battery ESS were the most used DERs. This is perhaps because of their relatively easier installation and accessibility to the general consumer. However, whereas PV is a non-dispatchable power source, batteries are often used as controllable sources to maintain stability in the microgrid. They have been used in the grid-connected mode for general cost reduction or load shifting. In the islanded mode of operation, they were usually used for backup power during low production hours from other DERs, serving as the grid-forming DER, and in some cases, for a black start operation.

The nature of the MG and area of installation would also affect the choice of DER installed. For instance, large-scale and rural microgrids are more likely to install wind power than urban and small-scale residential microgrids, which would be more likely to go for rooftop solar PV installation. Moreover, depending on the areas of installation and the nature of the study, wind power has also been used extensively in microgrids. Another important DER employed is the diesel generator. Some studies have referred to these as the base generation for the islanded mode of operation and others as emergency generators to meet peak loads. This is mainly due to short startup timings and a stable and constant production profile. However, its downside is fuel costs and carbon emissions.

Microgrid topology and DER selection are considered within the scope of MG planning and design. Various factors must be considered when deciding on an MG architecture (X. Wei et al., 2018). In this regard, the foremost decision is whether to build an AC/DC or a hybrid microgrid. This further depends on various factors such as the nature of locally available power supply, type of loads, power infrastructure, etc (F. Khavari, 2020). For instance, if planning on transforming part of an existing AC distribution network into an MG, it would be best to use an AC Microgrid

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(Bazmohammadi,.wt al., 2020). On the other hand, if we are considering remote areas with no existing power supply and where fuel supply is also difficult, it would be better to opt for DC microgrids. This is because commonly used renewable sources are DC, and overall cost could be reduced by not considering AC-DC converters.
Moreover, decisions can be made based on the type of load to be fed, whether the microgrid is in the vicinity of or remote from a population center, and the local climate. Climate analysis determines the type of renewable generation to be deployed (Thirugnanam, et al., 2021). Furthermore, based on the purpose of the MG and proximity to existing distribution networks, it would have to be decided whether to adopt a grid-connected MG or an islanded system.
In recent literature, the concept of a multi-microgrid system has also been proposed (Chiu, et al., 2015, Wei et al., 2018, Khavari, 2020, (Bazmohammadi,.et al., 2020). The primary purpose of organizing such a structure is to further improve operational and economic performance, especially under disturbances occurring from intermittent renewable resources (Zhang et al., 2018). In such a system, microgrid- and multi-microgrid-level operations often have different objectives. For instance, in 2015, Chiu, et al., (2015), a distribution network operator (DNO) handles the multi-microgrid system with the aim of trading with the main grid to maximize revenue. Meanwhile, the objective of each microgrid is to maximize the overall net value derived from the power consumption that the DNO traded. For further study on the microgrid structures, reference is made to (Unamuno and Barrena, 2023).It provides a detailed review of widely used microgrid architectures mentioned in the literature, classified into AC, DC, and Hybrid architectures, and comparisons.

Microgrid Control Hierarchy

- Primary Control: Primary control stabilizes the microgrid immediately after disturbances, without relying on communication networks. It ensures that voltage and frequency deviations remain within acceptable limits.
- Droop Control: Droop control emulates the natural droop behavior of synchronous generators. For an inverter interfacing DER.

Advantages: simple, decentralized, communication-free.
Limitations: poor power-sharing accuracy under unequal line impedances, limited dynamic performance.

- Virtual Synchronous Machine (VSM) Control: VSM control provides synthetic inertia, emulating the swing equation of synchronous VSMs improve transient stability, frequency regulation, and load-sharing accuracy. However, they require higher computational resources and careful parameter tuning.
- **Secondary Control:** Secondary control restores voltage and frequency deviations to nominal values and corrects power-sharing mismatches caused by primary droop control.
- **Centralized Secondary Control:** The controller calculates global voltage/frequency deviations and sends reference
- **Distributed/Consensus-Based Control:** Distributed control is more resilient to communication failures and better suited for community microgrids.
- **Tertiary Control:** Tertiary control manages energy optimization, economic dispatch, and interaction with the main grid.

Communications Network

A microgrid requires a communication network to enable data transfer between the various microgrid components. A good communication network ensures effective monitoring and control of the multiple DERs and loads connected to the system. Moreover, microgrids require resilient communication networks to enable rapid fault clearing and improve stability in islanding incidents.
Communication topologies can be categorized mainly into centralized and distributed systems (S. Marzal, et al 2018). A centralized topology uses a central server that accumulates monitoring data from the other components and provides control signals after processing, acting as a central master coordinating all the other clients in the network. A distributed system has computing capability within each DER and shares the information either with each other in a meshed structure or to a central server in the microgrid. A detailed review of the communication methods used in a microgrid was presented in (Thirugnanam, et al., 2021).
One crucial issue to consider is cyber-security in microgrids since these systems increasingly rely on information and communication technologies (Gaggero, et al., 2021). The cyber and physical processes in smart microgrids are tightly

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coupled, exposing them to a wide range of cyber-attacks. These vulnerabilities may destroy critical MG infrastructure and the economy (Nejabatkhah,et al., 2021, Jamil, et al., 2021). Several potential examples of cyber-attacks have been identified in the literature. One such type is the Spoofing attack on Internet-of-Things (IoT) enabled EV charging stations, where the charging and thermal management systems can be manipulated to bypass cable cooling functions. This can become a fire-hazard and potentially endanger public safety (Nejabatkhah,et al., 2021).
A cyber-attack on DERs can also result in a loss of revenue when dispatchable sources become unavailable or do not perform according to the optimally scheduled power exchange determined by the EMS. This can happen due to false-data-injection attacks, where manipulated data is fed into the EMS, causing system failure or inefficient operation. In addition, there can be attacks on data availability at critical times in various MG components. For instance, data transfer to protection relays can be delayed, proving catastrophic during power faults. Moreover, hackers can also exploit system vulnerabilities arising from co-habiting legacy and new systems (N. Jamil, et al., 2021).
Various steps can be taken to ensure safety from cyber-attacks. For example, the physical security of microgrid assets should be guaranteed, and proper personnel training on the safe use of sensitive assets should be done periodically. Additionally, plans for system recovery should be established to minimize system downtime. Moreover, various cyber-security technologies developed in the last few years to protect industrial control systems should be implemented and updated. These technologies include establishing and managing cryptographic keys in Advanced metering infrastructure (AMI) components and power converters for secure data transfer, security monitoring systems, and control strategies that are resilient to cyber-attacks.

Energy Management and Control System
An EMCS is an integral part of a microgrid, mainly because of the distributed nature of its energy resources. An EMCS aims to optimize the usage of the different resources to achieve specified objectives within system constraints through centralized, decentralized, or distributed computation. Secondly, the EMCS must effectively apply the previous computations to the microgrid system. This is achieved using a real-time control system that involves the operation set points generated by the EMCS. Most EMCS often work in a flow that includes forecasting data, feeding the results to EM optimization, and producing operational set points to be implemented by the real-time control stage. This section outlines various EMCS structures and highlights their operational flow in microgrids. An EMCS aims to optimize the usage of the different resources to achieve specified objectives within system constraints through centralized, decentralized, or distributed computation. Secondly, the EMCS must effectively apply the previous computations to the microgrid system. This is achieved using a real-time control system that involves the operation set points generated by the EMCS. Most EMCS often work in a flow that includes forecasting data, feeding the results to EM optimization, and producing operational set points to be implemented by the real-time control stage

CONCEPTUAL FRAMEWORK:

Several issues have been reported with the expansion of the electric power grid and the increasing use of intermittent power sources, such as the need for expensive transmission lines and the issue of cascading blackouts, which can adversely affect critical infrastructures. Microgrids (MG) have been widely accepted as a viable solution to improve grid reliability and resiliency, ensuring continuous power supply to loads. However, to ensure the effective operation of the Distributed Energy Resources (DER), Microgrids must have Energy Management and Control Systems (EMCS). Therefore, considerable research has been conducted to achieve smooth profiles in grid parameters during operation at optimum running cost.
Microgrid energy management and control strategies are typically organized into a hierarchical structure comprising primary, secondary, and tertiary control layers (Zhang, et al., 2019), each serving distinct functions to ensure stable, efficient, and reliable operation (Strasser, et al., 2019). The primary control stage is responsible for immediate, real-time regulation of voltage and frequency within the microgrid (Liu, et al., 2020). Common techniques at this stage include droop control for power sharing among distributed generators, virtual synchronous machine (VSM) control for emulating synchronous generator dynamics, and inverter-based local controllers (Yazdanian and Iravani, 2016). Primary control operates autonomously without communication dependencies, providing fast response to load fluctuations and ensuring basic stability of the microgrid.
The secondary control stage focuses on correcting deviations caused by the primary control layer and restoring system parameters to nominal values (Meng, et al., 2018). This includes frequency restoration, voltage regulation, and

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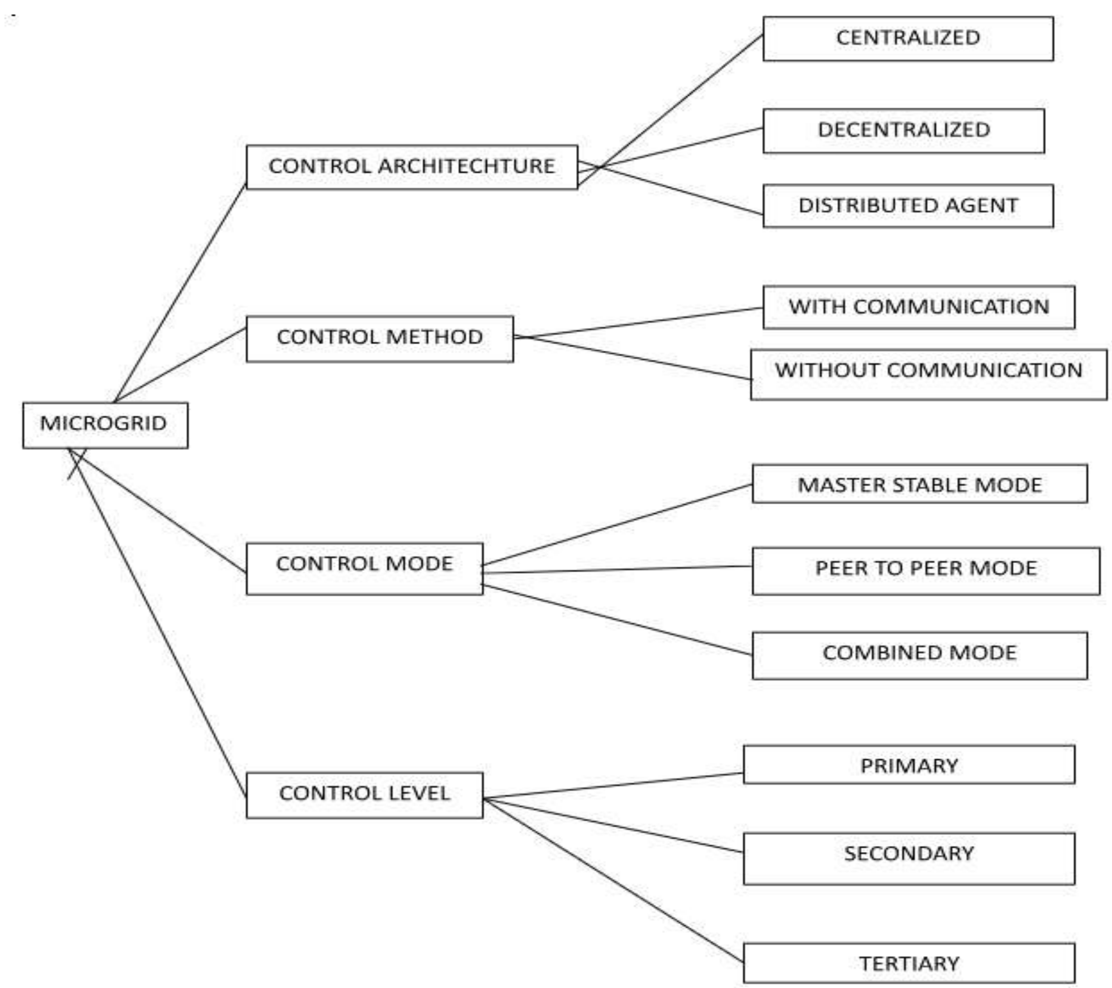
coordinated reactive power sharing. Secondary control can be implemented using centralized, distributed, or multi-agent system (MAS) approaches, depending on the complexity of the microgrid (Guerrero, et al, 2013). Distributed strategies and MAS are particularly advantageous in improving resilience and fault tolerance, as they allow controllers to communicate and coordinate locally without relying on a single point of failure.

The tertiary control stage addresses economic and operational optimization of the microgrid, often coordinating with the main grid if connected. This layer handles energy management, including scheduling generation, storage dispatch, and load management to minimize operational costs and maximize renewable energy utilization (Mahmud, et al., 2021). Advanced methods such as model predictive control (MPC) are commonly applied at this stage to predict future load and generation profiles and optimize control actions over a finite horizon, ensuring both reliability and cost efficiency (Meng, et al., 2019).

In addition to the hierarchical layers, hybrid and integrated control strategies combine features from multiple approaches to enhance microgrid performance (Zhang, et al., 2019). For instance, a combination of droop, VSM, and MPC can simultaneously provide fast dynamic response (Wu, et al., 2017), high power-sharing accuracy, and predictive optimization. These stages collectively form a comprehensive energy management framework that balances stability, efficiency, and flexibility, adapting to the specific requirements of industrial or community microgrids (Mollaghasemi and Ardehali 2018).



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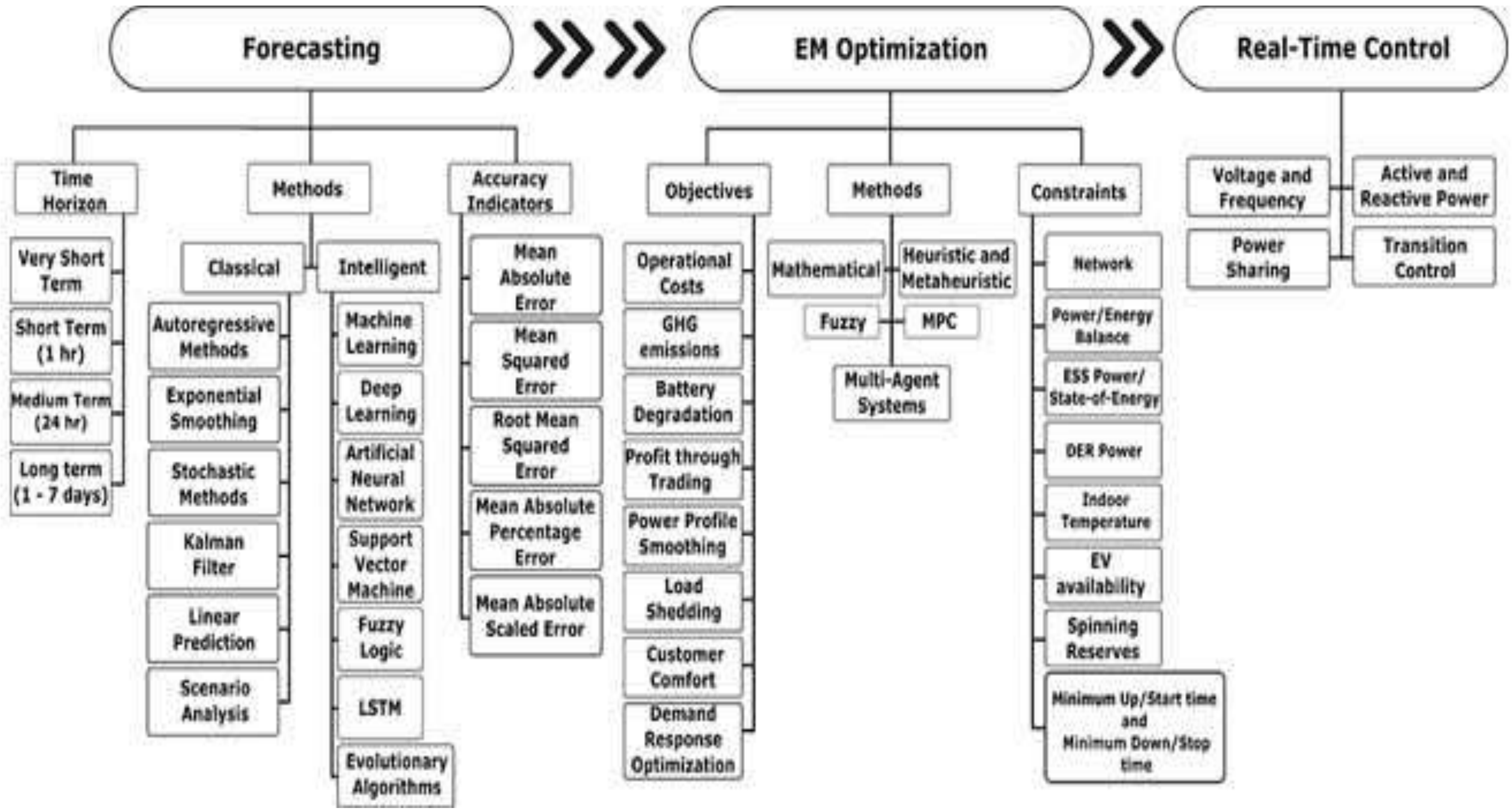

Stages of Microgrid Energy Management and Control Strategie

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SCOPE

This study focuses on the comprehensive analysis of microgrid energy management and control strategies, highlighting their stages, operational roles, and suitability for industrial and community energy systems. The research covers the three primary stages of microgrid control: primary, secondary, and tertiary control, along with the evaluation of advanced and hybrid strategies such as droop control, virtual synchronous machines (VSM), model predictive control (MPC), hierarchical control, and multi-agent system (MAS)-based approaches**.**

The study emphasizes the functional requirements of microgrids, including power quality, reliability, renewable energy integration, and system stability, while assessing how control strategies address these needs in both industrial and community contexts. Special attention is given to islanding operations**,** battery energy storage management, and predictive optimization to ensure continuous operation during grid disconnection or disturbances. The research also considers real-time operational factors, such as communication reliability, dynamic response to load variations, and control coordination among distributed energy resources (DERs).

The scope includes theoretical modeling, performance evaluation, and comparative analysis of control strategies, focusing on their impact on system stability, frequency and voltage regulation, power-sharing accuracy, and renewable energy utilization. While the study provides detailed insights into control algorithms and energy management frameworks, it is limited to conceptual and simulation-based analyses**,** without full-scale experimental validation or hardware implementation. Additionally, the research focuses primarily on microgrids with a combination of renewable and conventional energy sources and does not extensively cover specialized microgrids such as isolated rural or military systems.

By addressing these areas, the study provides a clear understanding of the stages of microgrid energy management, identifies the most effective control strategies for specific applications, and offers guidance for system designers, operators, and policymakers to enhance microgrid reliability, efficiency, and flexibility.

METHODOLOGY

This study adopted a systematic review methodology guided by the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021). Systematic reviews are widely used in engineering research to ensure a transparent, structured, and replicable approach to identifying, evaluating, and synthesizing existing evidence. This methodology minimizes bias and strengthens the reliability of conclusions regarding the state of knowledge on microgrid energy management and control strategies. The focus of this review was on peer-reviewed literature published between 2000 and 2025 examining the stages of microgrid control primary, secondary, and tertiary control as well as advanced methods such **as** droop control, virtual synchronous machines (VSM), model predictive control (MPC), hierarchical and distributed control architectures, multi-agent systems (MAS), and hybrid control strategies. The goal was to identify the operational principles, performance characteristics, challenges, and research gaps associated with these strategies in both industrial and community microgrid settings.

The review included only studies that met strict eligibility criteria. Eligible publications were peer-reviewed journal articles written in English between 2000 and 2025 and focusing on microgrids incorporating renewable energy sources, battery energy storage systems (BESS), power electronics, or distributed generation. To be included, studies needed to provide empirical or simulation-based evidence on microgrid control strategies addressing frequency regulation, voltage stability, energy optimization, islanding behavior, communication requirements, or resilience. Studies employing experimental, analytical, simulation, or hybrid methodologies were considered. Excluded studies included conference abstracts without full papers, studies unrelated to microgrid control (e.g., macro-grid planning), papers lacking empirical or simulation data, and grey literature such as reports, theses, and unpublished manuscripts. These criteria ensured that only high-quality, relevant, and recent research was synthesized.

A comprehensive search strategy was executed across major engineering and energy databases, including IEEE Xplore, ScienceDirect, Scopus, Web of Science, SpringerLink**,** and Energy Database, with additional searches conducted in Google Scholar to capture interdisciplinary works related to optimization, forecasting, communication systems, and control theory. Boolean search strings combined terms such as: “microgrid control,” “primary control,” “secondary control,” “tertiary control,” “droop control,” “VSM,” “MPC,” “hierarchical control,” “distributed control,” “multi-agent systems,” “islanding,” “renewable energy integration,” “battery management,” and “frequency-voltage

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stability." Reference lists of key papers were manually screened, and leading journals were hand-searched to ensure completeness. Duplicate records were removed prior to screening.
The study selection procedure followed a two-stage PRISMA screening process. First, two independent reviewers screened titles and abstracts to eliminate studies clearly outside the topic area, such as works on large-scale grids, building-level energy management, or unrelated control fields. Next, full texts of potentially eligible studies were retrieved and evaluated, with exclusion decisions documented. Disagreements were resolved through discussion or review by a third expert to minimize selection bias. The final selection process is documented using a PRISMA flow diagram.

Identification Phase
A total of 520 records were identified through database searches across IEEE Xplore, Scopus, Science Direct, Web of Science, Springer Link, and Energy Database. An additional 60 records were discovered through reference list checks and manual journal searches. After removing 80 duplicates, 500 unique records remained for screening.

Screening Phase
Titles and abstracts of the 500 unique records were screened. 210 records were excluded for reasons such as irrelevance to microgrids, focus on utility-scale grids, studies on electric vehicles, or articles lacking technical control components. After screening, 290 full-text articles remained for detailed assessment.

Eligibility Phase
During the eligibility phase, a full-text assessment of the 290 articles led to the exclusion of 190 studies for several specific reasons. Seventy-five studies were excluded because they did not directly address microgrid control strategies, while forty lacked empirical or simulation-based evidence necessary for inclusion. Thirty-two articles focused on energy management topics unrelated to the scope of microgrid control. Twenty-five studies fell outside the required publication timeframe of 2010 to 2025, and eighteen were review papers that did not provide original data. After applying these criteria, a total of 100 studies met all eligibility requirements and were included in the final synthesis.

Included Studies Phase
A total of 100 peer-reviewed studies published between 2000 and 2025 were included in the qualitative synthesis. Due to methodological heterogeneity across studies concerning control algorithms, test systems, simulation tools, and performance metricsa quantitative meta-analysis was not feasible. Therefore, a narrative synthesis was conducted to analyze trends, classify control strategies, and identify research gaps across microgrid energy management literature.

LIMITATIONS

A review of existing literature on microgrid energy management and control strategies reveals several limitations that highlight opportunities for further research.
Firstly, most studies focus on simulation-based analyses of control strategies, with limited experimental validation on real-world microgrid systems. This raises concerns regarding the practical applicability of proposed algorithms, particularly under dynamic load conditions and real-time disturbances.
Secondly, many works consider ideal communication networks and do not fully account for delays, packet loss, or failures in decentralized or multi-agent system (MAS) architectures. Such assumptions may overestimate the performance and stability of microgrid control strategies in practical implementations.
Thirdly, while renewable energy integration is often discussed, few studies incorporate battery degradation costs, lifecycle analysis, or economic optimization comprehensively. Neglecting storage lifecycle management can lead to suboptimal scheduling and increased operational costs over time.
Additionally, islanding operations are sometimes oversimplified or not rigorously tested, yet islanded mode constitutes a core feature of microgrids. The lack of detailed studies on fault-tolerance, emergency backup coordination, and hybrid generation scenarios limits the understanding of microgrid reliability under contingencies.

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Furthermore, many studies focus primarily on industrial or high-capacity microgrids, neglecting community-scale applications, where cost constraints, modular expansion, and simpler architectures are critical. Similarly, most research assumes short-term forecasting and does not address the uncertainty and variability of renewable generation over longer horizons.

Finally, comparative evaluations across multiple control strategies are limited, with insufficient work assessing trade-offs between performance, complexity, cost, and scalability. Addressing these limitations is essential for designing robust, efficient, and economically viable microgrid control strategies suitable for diverse applications.

FINDINGS

1. **Differences Between Industrial and Community Microgrids in Load, Reliability, Renewable Penetration, Demand Patterns, and Regulatory Constraints**

Industrial and community microgrids differ significantly across multiple dimensions: load characteristics, reliability requirements, renewable energy penetration, demand patterns, and regulatory frameworks. Industrial microgrids prioritize stability, predictable loads, and operational continuity, with renewables serving a supplementary role. Community microgrids, on the other hand, emphasize flexibility, renewable integration, cost optimization, and adaptability to stochastic demand profiles. Regulatory considerations further differentiate the two, with industrial microgrids often subject to strict safety and reliability standards, while community microgrids must balance technical performance with social, environmental, and policy-driven objectives. Recognizing these differences is essential for selecting control strategies—such as droop, MPC, RL, or hybrid approaches—that align with each microgrid's operational priorities and constraints, ensuring both technical efficacy and economic viability (Almihat & Munda, 2023; Li et al., 2023; Yao et al., 2023).

Microgrids are localized energy systems designed to integrate distributed energy resources (DERs), storage systems, and controllable loads, providing enhanced resiliency, efficiency, and flexibility compared to conventional grid arrangements (Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023). However, microgrids are not homogenous; their operational characteristics and design priorities differ substantially depending on whether they serve industrial facilities or community-scale energy systems. Understanding these differences is critical for selecting appropriate control strategies, optimizing system performance, and aligning operational decisions with economic, technical, and social objectives.

1. Load Characteristics

One of the most significant distinctions between industrial and community microgrids lies in their load characteristics. Industrial microgrids primarily support manufacturing facilities, chemical plants, data centers, or other mission-critical operations where energy demand is high, continuous, and often predictable (Almihat & Munda, 2023). For instance, a semiconductor manufacturing facility may require uninterrupted power with extremely tight voltage and frequency tolerances, as even minor deviations can damage sensitive equipment. Load patterns in industrial settings are typically dominated by a few large, centralized loads, although some industries experience short-duration peak demands during equipment start-up or batch operations. This high concentration of load demands results in large short-circuit levels, which influence protection system design and control strategy requirements.

In contrast, community microgrids serve a diverse mix of residential, commercial, and small institutional users. Their load profile is highly variable and often stochastic, reflecting household activity patterns, business hours, and seasonal changes (Hu et al., 2021). Peaks typically occur in the morning and evening residential usage periods, while commercial load contributions are highest during daytime hours. Additionally, community microgrid loads may include smaller electric vehicles, smart appliances, and localized heating/cooling systems, adding layers of variability and unpredictability. The diversity of loads in community microgrids necessitates more flexible control mechanisms that can respond dynamically to fluctuating demand.

2. Reliability Requirements

Reliability is another key differentiator. Industrial microgrids place extreme importance on uninterrupted operation because power outages can have significant economic and operational consequences. For example, a chemical

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processing plant experiencing a power failure may face product losses, equipment damage, or safety hazards, translating into substantial financial and reputational costs. As a result, industrial microgrids are often designed with redundant generation sources, fast-acting controllers, and fault-tolerant configurations to ensure continuous operation (Almihat & Munda, 2023). The system must also respond rapidly to disturbances, maintaining voltage and frequency within tight tolerances.

Community microgrids, while also valuing reliability, generally have more relaxed constraints**.** Interruptions may be tolerated for non-critical residential loads or small commercial facilities, particularly if they occur infrequently. Community systems often prioritize cost and environmental performance over absolute reliability**,** focusing backup generation and storage primarily on critical loads such as hospitals, emergency services, or community infrastructure (Energies, 2023). Consequently, reliability strategies in community microgrids may incorporate demand response, energy storage, and selective load shedding, providing resilience without the same level of redundancy as industrial systems.

3. Renewable Energy Penetration

Community microgrids are generally designed to maximize renewable energy integration**,** such as solar photovoltaic (PV) arrays, wind turbines, or small-scale biomass systems. High renewable penetration is attractive in community settings because it reduces electricity costs, lowers carbon emissions, and promotes energy self-sufficiency. However, renewable energy sources introduce variability and uncertainty, which must be carefully managed through storage systems, predictive control, and adaptive energy management strategies (Chaturvedi et al., 2023).

In industrial microgrids, renewable adoption tends to be more conservative. While many industrial facilities incorporate solar or combined heat and power systems, the primary driver is ensuring continuous, high-quality power rather than maximizing renewable usage. Industrial microgrids often rely on dispatchable generation sources such as diesel or natural gas generators to maintain supply during periods of renewable intermittency. In these settings, renewable sources complement conventional generation rather than serving as the primary source of energy, ensuring that operational continuity is never compromised (Yao, Zhao, Forshaw & Song, 2023).

4. Demand Patterns

Demand patterns further distinguish industrial and community microgrids. Industrial loads are typically predictable in magnitude and timing**,** governed by production schedules, shift operations, or batch processes. Peaks are usually known in advance, allowing operators to plan generation dispatch and storage operation effectively (Hu et al., 2021). Some industrial processes, however, require highly dynamic responses during equipment startup or shutdown, necessitating fast control loops and robust stabilization mechanisms.

Community microgrids, in contrast, face stochastic and variable demand patterns**.** Residential demand fluctuates based on human behavior, appliance use, and even cultural practices, while commercial loads vary with business operations. Seasonal changes also introduce variability, such as increased air conditioning loads in summer or heating in winter. These dynamic and often unpredictable patterns require adaptive energy management strategies**,** including predictive forecasting, demand response, and real-time optimization of generation and storage assets (Li et al., 2023). Moreover, community microgrids must handle smaller, distributed loads, which can collectively contribute to significant demand fluctuations.

5. Regulatory Constraints

Regulatory frameworks play a significant role in shaping microgrid design and operation. Industrial microgrids often operate under less stringent regulatory oversight**,** especially when owned and managed privately for self-consumption. However, they are typically subject to strict reliability, safety, and interconnection standards due to the potential consequences of outages or grid disturbances. For example, industrial microgrids may need to comply with IEEE 1547 standards for interconnection or local safety codes.

Community microgrids, by contrast, face more complex regulatory environments**.** They must often integrate with public utility grids, comply with tariff regulations, and participate in renewable energy incentive programs. Regulatory policies may also require equitable access, prioritization of renewable integration, and support for grid services such

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as demand response or ancillary services (Chaturvedi et al., 2023). This complexity adds layers of planning and operational considerations that are less prominent in private industrial microgrids.

2. Designing Representative Simulation Models for Industrial and Community Microgrids

Designing representative simulation models for industrial and community microgrids requires careful integration of realistic load profiles, generation assets, storage systems, and grid interaction settings. Industrial microgrids demand high-fidelity modeling of large, centralized loads, dispatchable generation, and resilient storage to support mission-critical operations. Community microgrids, by contrast, require stochastic modeling of diverse and variable loads, high renewable penetration, distributed storage, and compliance with grid-interactive and regulatory constraints. Simulation modeling plays a critical role in the design, evaluation, and optimization of microgrids. By accurately representing the physical and operational characteristics of industrial and community energy systems, simulation models provide a safe and cost-effective platform for testing control strategies, evaluating economic performance, and predicting system behavior under various disturbances (Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023). Designing representative models requires careful consideration of four key aspects: realistic load profiles, generation assets, energy storage systems, and grid-interaction settings. Each component must reflect the operational priorities and variability inherent in the target microgrid type.

1. Load Profile Integration

Load modeling is the foundation of any microgrid simulation. For industrial microgrids, load profiles are typically high-magnitude, centralized, and predictable, driven by manufacturing schedules, continuous-process operations, or mission-critical infrastructure. Accurate modeling requires detailed data on equipment ratings, operational schedules, and transient behavior during startup, shutdown, and process transitions. For example, an industrial microgrid supplying a data center must account for constant base loads from server racks, intermittent loads from cooling systems, and occasional peak loads during high computational demand (Almihat & Munda, 2023). Modeling these profiles enables simulation of voltage stability, frequency response, and fault-handling performance under real operating conditions.

Community microgrids, by contrast, serve a diverse mix of residential, commercial, and institutional loads, leading to highly variable and stochastic demand patterns. Load modeling for community systems typically involves aggregating individual household and commercial load profiles derived from smart meter data, census information, or national load statistics. Temporal resolution is crucial: minute-level or second-level data may be required to capture short-term fluctuations in demand caused by appliance usage, electric vehicle charging, or demand response events (Hu et al., 2021). Stochastic load generation techniques or probabilistic models can simulate variability and uncertainty, which is particularly important for testing adaptive control strategies like model predictive control (MPC) and reinforcement learning (RL).

2. Generation Asset Modeling

Generation assets in microgrid simulations include renewable sources (solar PV, wind, small hydro), conventional generators (diesel, gas turbines, microturbines), and, in some industrial systems, combined heat and power (CHP) units. For industrial microgrids, dispatchable generators are often the backbone of the system to maintain reliability and power quality. Renewable integration is typically secondary and must be coordinated with storage and dispatchable units to avoid voltage or frequency instability (Yao, Zhao, Forshaw & Song, 2023).

Community microgrids, on the other hand, frequently emphasize high renewable penetration, including rooftop solar, community wind farms, and bioenergy. Modeling these resources requires incorporating weather-dependent generation patterns using historical irradiance, wind speed, or seasonal load data. It is also essential to account for variability and intermittency through probabilistic generation models or scenario-based simulations (Chaturvedi et al., 2023). For both industrial and community systems, generator models must include electrical characteristics (voltage-current relationships, reactive power capabilities), dynamic response to control inputs, and operational constraints such as ramp rates, minimum up/down times, and fuel limitations.

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3. Energy Storage Systems

Energy storage systems (ESS) are critical components in microgrid simulations, particularly for balancing supply-demand mismatches, improving resilience, and enabling renewable integration. Industrial microgrids often require high-capacity batteries or flywheel storage to support critical loads during disturbances or blackouts, with stringent requirements on response time and state-of-charge management. Accurate modeling of ESS includes battery dynamics (charge/discharge efficiency, state-of-charge limits, degradation rates), inverter characteristics, and control interactions with other generation units (Almihat & Munda, 2023).

Community microgrids may rely on smaller-scale distributed storage, such as residential batteries, aggregated virtual storage, or community-scale systems, to enhance renewable utilization and support grid interactions. In simulations, storage modeling must capture both energy management objectives (e.g., peak shaving, load shifting) and operational constraints, such as cycling limitations and inverter efficiency losses (Energies, 2023). Integrating realistic ESS models enables evaluation of the techno-economic performance of control strategies under varying load and generation scenarios.

4. Grid-Interaction Settings

Modeling the interaction between microgrids and the main grid is essential for both industrial and community systems. Industrial microgrids may operate in grid-connected mode most of the time, with islanding capability for resilience. Accurate simulation requires modeling point-of-common coupling (PCC) characteristics, fault dynamics, synchronization behavior, and protective relay coordination. Scenarios such as grid outages, voltage sags, or frequency excursions must be incorporated to test control performance and fault-handling capabilities (Li et al., 2023).

Community microgrids, particularly those integrated into urban or rural distribution networks, must simulate both grid support services and compliance with regulatory constraints. This includes reactive power support, demand response participation, net-metering policies, and tariff structures. Models may need to consider multiple points of interconnection, local voltage regulation, and dynamic pricing schemes. Accurately representing grid-microgrid interactions allows for testing of economic dispatch strategies, renewable integration efficiency, and resilience under grid disturbances.

5. Simulation Platforms and Implementation Considerations

Selecting an appropriate simulation environment is critical. Common platforms include MATLAB/Simulink, DIgSILENT PowerFactory, and OpenDSS, each offering unique advantages:

- MATLAB/Simulink provides flexible modeling of control algorithms, integration of renewable and storage models, and visualization of system dynamics. It is particularly suited for testing advanced control strategies like MPC and RL.
- DIgSILENT PowerFactory excels in detailed electrical network simulation, including protection coordination, fault analysis, and voltage stability. It is often preferred for industrial microgrid studies.
- OpenDSS is suitable for community-scale simulations, especially for integrating large numbers of distributed generation units and analyzing power flows, losses, and voltage profiles.

Simulation models should incorporate **multi-level temporal resolutions**, including fast dynamics (milliseconds to seconds) for control response and slower dynamics (minutes to hours) for energy management and economic evaluation. Sensitivity analyses and Monte Carlo simulations can be conducted to assess robustness under variability in loads, generation, and storage availability (Hu et al., 2021).

6. Integration and Validation

To ensure representativeness, simulation models must integrate all components load, generation, storage, and grid interactions—into a unified platform. Validation is critical, using either historical operational data or published benchmarks to ensure the model accurately reflects real-world behavior. Industrial microgrid models may be validated against factory energy logs, while community microgrid models may use smart meter data or publicly available load profiles. Proper validation ensures that results from simulation studies, including control strategy evaluations, techno-economic assessments, and resilience analyses, are reliable and actionable.

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3. Impact of Control Strategies on Microgrid Performance Metrics

control strategy impacts microgrid performance metrics differently. Droop and hierarchical control excel in simplicity, fast response, and low computational requirements but may compromise energy efficiency, power quality, and dispatch optimization. MPC provides predictive, constraint-aware optimization, improving voltage and frequency stability, energy efficiency, and dispatch accuracy but demands high computational resources. RL-based strategies offer adaptive, data-driven optimization, enhancing resilience and efficiency in uncertain environments but requiring substantial training and data. Hybrid approaches leverage the strengths of each method, providing a balanced performance across metrics and suitable adaptability for both industrial and community microgrids. Microgrid control strategies play a crucial role in maintaining system stability, efficiency, and reliability under variable operating conditions. Common strategies include droop/hierarchical control, Model Predictive Control (MPC), Reinforcement Learning (RL)-based control, and hybrid approaches that combine multiple methods. Each strategy exhibits distinct characteristics in terms of performance metrics such as frequency and voltage stability, energy efficiency, reliability indices, power quality, dispatch accuracy, computational complexity, and resilience to disturbances (Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023).

1. Frequency and Voltage Stability

Droop-based and hierarchical control methods are widely used in both industrial and community microgrids because of their simplicity and robustness. Droop control regulates active and reactive power sharing among parallel generators by adjusting frequency and voltage setpoints, ensuring basic load sharing without requiring communication (Almihat & Munda, 2023). While effective for small disturbances, droop control may exhibit steady-state deviations in frequency and voltage, particularly under large load changes or high renewable penetration. Hierarchical extensions, such as secondary and tertiary control layers, mitigate these deviations through corrective adjustments, improving voltage regulation and frequency restoration.

MPC offers predictive and optimization-based control, maintaining voltage and frequency within tight limits by forecasting system behavior over a finite horizon (Hu et al., 2021). MPC can accommodate constraints on generation, storage, and loads, providing superior dynamic performance compared to droop control, especially in microgrids with high renewable penetration. RL-based controllers, using data-driven learning, adaptively optimize frequency and voltage stability over time, particularly under nonlinear and uncertain operating conditions, though training periods and computational demands can limit real-time deployment.

Hybrid strategies combine the robustness of droop control with the predictive and adaptive advantages of MPC or RL, achieving both immediate response to disturbances and optimal performance under variable conditions (Yao, Zhao, Forshaw & Song, 2023).

2. Energy Efficiency

Energy efficiency in microgrids is influenced by how effectively control strategies manage generation, storage, and load dispatch. Droop and hierarchical control tend to prioritize stability over efficiency, leading to higher operating losses during light-load or intermittent renewable periods. MPC optimizes energy dispatch by forecasting demand and renewable availability, reducing fuel consumption and improving utilization of storage and renewable assets (Chaturvedi et al., 2023). RL-based control can further enhance efficiency by learning optimal policies from historical operational data, minimizing unnecessary generator cycling and storage losses.

3. Reliability Indices

Reliability metrics, including loss of load probability (LOLP) and system average interruption duration index (SAIDI), are critical for evaluating industrial and community microgrids. Droop-based systems provide fast local response, improving reliability under minor disturbances but may struggle with complex multi-source coordination. MPC improves reliability by anticipating potential imbalances and proactively adjusting resources, while RL-based controllers enhance long-term reliability by adapting to patterns of faults, renewable intermittency, and load variability (Li et al., 2023).

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4. Power Quality
Power quality metrics, such as voltage sags, harmonics, and total harmonic distortion (THD), are particularly important in industrial microgrids with sensitive equipment. Droop control may lead to voltage fluctuations and harmonic distortions during large load variations. MPC's predictive adjustment of voltage and reactive power can mitigate such fluctuations effectively, while RL can optimize inverter control to minimize harmonics in real time. Hybrid approaches often achieve the best balance, using fast droop responses to maintain basic stability and MPC/RL layers to fine-tune voltage and power quality (Almihat & Munda, 2023).

5. Dispatch Accuracy
Dispatch accuracy refers to the ability to allocate generation and storage resources optimally to meet load demand. Droop control provides basic proportional allocation without optimization, which may result in sub-optimal dispatch under variable loads. MPC achieves high dispatch accuracy by solving constrained optimization problems over forecast horizons, ensuring minimal cost and efficient resource utilization. RL-based controllers can learn dispatch strategies that adapt to seasonal or stochastic patterns, improving performance in uncertain environments (Hu et al., 2021).

6. Computational Complexity
Droop and hierarchical control are computationally lightweight, making them suitable for microgrids with limited communication or processing resources. MPC requires significant computational resources for solving optimization problems in real time, which can be challenging for large-scale or fast-response systems. RL-based controllers have high training complexity but can offer near-optimal real-time performance once trained. Hybrid strategies balance computational demands by leveraging droop control for fast response while invoking MPC/RL only for slower, high-level optimization tasks (Yao et al., 2023).

7. Resilience to Disturbances
Resilience, or the ability to maintain performance under faults, load spikes, and renewable intermittency, varies across control strategies. Droop control provides immediate, decentralized response to small disturbances, ensuring continued operation but limited adaptability to major faults. MPC anticipates disturbances and allocates resources proactively, enhancing microgrid resilience under predictable scenarios. RL-based controllers improve resilience over time by learning from repeated disturbances, offering adaptive strategies to maintain stability and optimize recovery. Hybrid approaches typically deliver the highest resilience, combining immediate droop responses with predictive or adaptive layers that mitigate both short-term and long-term disruptions (Chaturvedi et al., 2023).

4. Suitability of Microgrid Control Strategies for Industrial and Community Applications
Selecting an appropriate control strategy for microgrids depends heavily on the operational priorities and technical characteristics of the system. Both industrial and community microgrids have distinct requirements; however, certain objectives such as flexibility, affordability, and effective renewable energy integration are increasingly relevant for both types of microgrids, especially in modern energy systems emphasizing sustainability and resilience (Li, Oshnoei, Blaabjerg & Anvari-Moghaddam, 2023). industrial and community microgrids prioritizing flexibility, affordability, and effective renewable integration, hybrid control strategies combining droop, MPC, and RL are generally the most suitable. Droop control ensures fast and reliable local responses, MPC provides predictive optimization for efficient resource utilization, and RL offers adaptive learning capabilities for uncertain and dynamic environments. Individually, MPC and RL excel in flexibility and renewable integration but may be limited by cost or computational demands, while droop control is affordable and simple but less optimal for variable conditions.

1. Flexibility
Flexibility refers to the system's ability to adapt to variable demand, intermittent renewable generation, and grid disturbances. Community microgrids typically feature highly stochastic loads and a large share of variable renewable energy sources such as solar PV and wind, necessitating responsive and adaptive control (Hu et al., 2021). Similarly,

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modern industrial microgrids increasingly integrate renewables and demand-side management, requiring adaptable control to balance efficiency and reliability.

Droop-based control provides fast, decentralized response and inherent load-sharing among generators without requiring high levels of communication. While this ensures basic operational flexibility during small fluctuations, droop control is less effective for handling highly variable renewable generation or complex multi-node energy systems. Hierarchical extensions improve flexibility by incorporating secondary and tertiary control layers that adjust generation and storage dispatch according to broader system objectives (Almihat & Munda, 2023).

MPC is highly suited to flexible operations because it can anticipate system behavior over a defined prediction horizon, adjusting generator outputs, storage dispatch, and load participation dynamically. MPC handles variable renewable generation efficiently by incorporating forecasts of solar irradiance, wind speed, and load profiles into optimization routines. Reinforcement learning further enhances flexibility by learning adaptive policies from historical data, enabling real-time adjustments to fluctuating demand and intermittent renewable output (Chaturvedi et al., 2023). Hybrid approaches, which combine fast droop responses for immediate load changes with MPC or RL layers for predictive and adaptive optimization, are particularly effective for ensuring both short-term and long-term operational flexibility.

2. Affordability

Affordability is determined by both capital costs and operational efficiency. Droop control is computationally simple and cost-effective, making it highly suitable for applications with limited financial or computational resources. Hierarchical droop control, which adds secondary and tertiary layers, incurs modest additional costs while improving performance.

MPC offers superior performance in terms of energy efficiency and optimal resource utilization, but its computational and implementation requirements are higher, which may increase upfront and operational costs. In community microgrids with distributed renewable resources, however, the savings achieved through optimized dispatch and reduced energy waste can justify the investment over time (Yao, Zhao, Forshaw & Song, 2023). RL-based control may involve significant initial investment in data acquisition, model training, and computing infrastructure, but it can reduce operational costs through adaptive optimization, particularly in systems with high variability.

Hybrid control strategies balance affordability and performance by using simple droop-based responses for immediate load regulation while activating MPC or RL only for high-level optimization tasks. This layered approach ensures that microgrids maintain operational efficiency without incurring excessive computational or hardware costs, making them suitable for both industrial and community contexts.

3. Effective Renewable Integration

Integrating variable renewable energy sources requires control strategies that can manage intermittency, maintain voltage/frequency stability, and coordinate storage and conventional generation. Droop control alone provides limited support for high renewable penetration because it lacks predictive capability, which can result in underutilization of renewables or over-reliance on dispatchable units. MPC excels in maximizing renewable utilization by forecasting output and scheduling storage or dispatchable generation accordingly, thereby reducing curtailment and enhancing energy efficiency (Hu et al., 2021). RL-based strategies can further improve renewable integration by learning optimal dispatch policies under variable generation and load conditions.

Hybrid control approaches are particularly advantageous for renewable-rich systems. For example, in a community microgrid with high solar PV penetration, a hybrid controller can use droop control for immediate load balancing, MPC for day-ahead or hour-ahead generation scheduling, and RL for adaptive learning under uncertain weather and demand conditions. In industrial microgrids, where reliability remains paramount, hybrid strategies enable the integration of renewables without compromising operational continuity.

5. Strengths, Limitations, and Practical Challenges of Microgrid Control Strategies

Microgrid control strategies determine how effectively distributed energy resources (DERs), energy storage systems (ESS), and loads are coordinated to maintain stability, reliability, and efficiency. Common approaches include

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droop/hierarchical control, Model Predictive Control (MPC), Reinforcement Learning (RL)-based control, and hybrid strategies. microgrid control strategy has specific strengths, limitations, and practical challenges. Droop and hierarchical control are robust, low-cost, and simple, but less efficient for renewable-rich systems. MPC provides predictive optimization and high performance, but at higher computational and implementation costs. RL offers adaptive and data-driven optimization for stochastic environments but faces challenges in safety, data requirements, and real-time deployment. Hybrid strategies combine the advantages of each, providing resilience, efficiency, and adaptability, but require careful design, tuning, and investment.

1. Droop and Hierarchical Control
Strengths:
Droop control is the most widely deployed strategy due to its simplicity, robustness, and decentralized nature. By regulating frequency and voltage in proportion to active and reactive power, droop control allows multiple generators to share load without requiring complex communication networks. This makes it highly reliable and fast-acting, suitable for both industrial microgrids with critical loads and community microgrids with moderate complexity. Hierarchical extensions—secondary and tertiary control layers—improve voltage and frequency restoration while maintaining the robustness of the primary droop loop (Almihat & Munda, 2023).

Limitations:
Despite its robustness, droop control has several limitations. First, it may introduce steady-state deviations in voltage and frequency, particularly under high renewable penetration or significant load changes. It also lacks predictive capability, making it less efficient in optimizing energy dispatch or storage utilization. Furthermore, droop-based systems may struggle with highly heterogeneous microgrids, where varying generator characteristics or load dynamics can lead to unequal power sharing.

Practical Challenges:
Real-world implementation challenges include tuning droop coefficients for optimal load sharing, integrating heterogeneous DERs with varying response times, and ensuring stability under fault conditions. In renewable-rich microgrids, the absence of predictive capabilities can lead to curtailment of excess generation or overuse of dispatchable generators (Hu et al., 2021). Additionally, communication and measurement errors can reduce accuracy in hierarchical layers, impacting overall performance.

2. Model Predictive Control (MPC)
Strengths:
MPC offers predictive optimization, using forecasts of load, renewable generation, and system constraints to schedule generation and storage optimally. This enables precise frequency and voltage regulation, improved energy efficiency, and effective renewable integration. MPC can handle multiple objectives simultaneously such as minimizing operational costs, maintaining power quality, and optimizing ESS dispatch making it well-suited for both industrial and community microgrids with complex dynamics (Chaturvedi et al., 2023).

Limitations:
MPC requires accurate system models, forecasts, and real-time computation. Inaccuracies in load or renewable forecasts can reduce performance, leading to sub-optimal dispatch. The method is also computationally intensive, which may limit its applicability in microgrids with limited processing resources or fast dynamic requirements.

Practical Challenges:
Implementing MPC in real-world microgrids involves high investment in sensing, communication, and computing infrastructure. Forecast errors, model uncertainties, and latency in measurement signals can degrade performance. Moreover, tuning MPC parameters, such as prediction and control horizons, requires significant expertise and may

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need ongoing adjustment as the system evolves (Li et al., 2023). Ensuring cyber-security and reliable communication channels is also critical to prevent disruptions.

3. Reinforcement Learning (RL)-Based Control
Strengths:
RL-based control is data-driven and adaptive, capable of learning optimal control policies over time without relying on explicit system models. It excels in handling stochastic and highly variable environments, making it ideal for community microgrids with high renewable penetration or industrial microgrids experiencing dynamic operational conditions. RL can optimize multiple objectives simultaneously, including energy efficiency, load balancing, and resilience, while improving performance as more operational data becomes available (Yao, Zhao, Forshaw & Song, 2023).

Limitations:
RL systems require extensive training data and computational resources, which can be a barrier to real-time deployment. During the learning phase, the system may exhibit sub-optimal or unstable behavior, which is unacceptable for industrial microgrids with critical loads. RL models may also overfit historical data, reducing their effectiveness under unforeseen scenarios or system changes.

Practical Challenges:
Key challenges include designing safe learning environments, acquiring high-quality data for training, and integrating RL controllers with existing microgrid infrastructure. Industrial operators may be hesitant to adopt RL due to its unpredictable behavior during the early learning stages. Additionally, RL systems require continuous monitoring and periodic retraining to accommodate system modifications or renewable capacity expansions.

4. Hybrid Control Strategies
Strengths:
Hybrid strategies combine the robustness and low computational demand of droop control with the predictive optimization of MPC and/or the adaptive learning of RL. This layered approach enables microgrids to respond quickly to disturbances, optimize energy dispatch, and improve renewable integration simultaneously. Hybrid control provides a balanced solution, making it suitable for microgrids that require both reliability and flexibility.

Limitations:
Hybrid systems can be complex to design and implement, requiring careful integration of multiple control layers. Coordination between different strategies may lead to conflicts or oscillatory behavior if not properly tuned.

Practical Challenges:
Real-world deployment requires high-level expertise in control engineering, forecasting, and data analytics. Communication networks must reliably transmit signals between layers, and system operators must manage interactions between fast droop responses and slower MPC/RL optimization. Cost considerations can also be significant, as hybrid controllers require investment in both hardware and software infrastructure (Almihat & Munda, 2023; Chaturvedi et al., 2023).

Industrial Microgrid Requirements
Industrial microgrids are designed to serve critical loads and must meet stringent power quality and reliability requirements. They require high reliability, which is typically measured through low SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) values, ensuring minimal downtime and interruption to essential operations. Additionally, industrial microgrids demand a fast dynamic response, as they are highly sensitive to rapid load changes, such as sudden motor starts or abrupt process variations, which could otherwise destabilize the system. High power-sharing accuracy is also essential to ensure that distributed

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generators share loads appropriately, preventing overloading of individual units and maintaining system stability. Furthermore, industrial microgrids aim for maximum utilization of renewable energy sources to reduce operational costs and minimize environmental impact, while maintaining reliability. Finally, they must adhere to stringent cybersecurity and safety standards to protect critical infrastructure from potential threats, ensure safe operation, and comply with industry regulations. These combined requirements make industrial microgrids highly sophisticated systems that demand advanced control strategies and careful planning to balance performance, resilience, and operational efficiency.

Strategy	Suitability	Notes
Droop	Limited	Cannot meet high accuracy or fast dynamics
VSM	High	Synthetic inertia ensures fast frequency response
MPC	High	Optimizes DER coordination and renewable penetration
Distributed/MAS	Moderate	Useful for fault tolerance but needs robust communication
Hierarchical/Hybrid	Very high	Integrates performance, resilience, and optimization

Community Microgrid Requirements

Community microgrids are primarily designed to serve residential neighborhoods, small businesses, or remote communities, and therefore they prioritize affordability, resilience, and operational simplicity. These systems require low-cost deployment, which involves minimal hardware requirements and limited communication infrastructure to keep installation and maintenance expenses manageable. Flexibility is also critical, as community microgrids must accommodate variability in renewable energy generation, such as solar and wind, while supporting modular expansion to allow additional resources or loads to be integrated over time. Additionally, community microgrids demand robustness, ensuring that they can continue operating effectively even in the event of communication failures or partial system faults. While high precision is less critical than in industrial applications, community microgrids still need moderate performance, maintaining acceptable frequency and voltage deviations to prevent damage to sensitive appliances while providing reliable energy supply. This balance between cost, simplicity, and acceptable performance makes community microgrids well-suited for decentralized energy access, supporting energy security and sustainability in small-scale or remote settings.

Strategy	Suitability	Notes
Droop	High	Simple, low-cost, decentralized
VSM	Moderate	High computation/cost may be a barrier
MPC	Limited	Requires computational resources and forecasts

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Strategy	Suitability	Notes
Distributed/MAS	High	Fault-tolerant and scalable
Hierarchical/Hybrid	Moderate	Complexity may not be justified

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SUMMARY

Control Strategy	Industrial Suitability	Community Suitability	Key Justification
Droop	Low	High	Simple, cost-effective
VSM	High	Moderate	Improves dynamics, higher cost
MPC	High	Limited	Predictive optimization, high computation
Distributed/MAS	Moderate	High	Fault-tolerant, decentralized
Hierarchical	Very High	Moderate	Optimized, integrates layers
Hybrid	Very High	Moderate	Best for critical performance

Summarily, Different microgrid control strategies exhibit varying degrees of suitability for industrial and community energy systems, depending on their complexity, cost, and performance characteristics. Droop control is highly suitable for community microgrids due to its simplicity, low cost, and ease of implementation; however, it is less suitable for industrial applications where higher precision and dynamic performance are required. Virtual Synchronous Machine (VSM) control demonstrates high suitability for industrial microgrids because it significantly improves system dynamics, enhances frequency and voltage stability, and mimics the behavior of synchronous generators, though its moderate suitability for community microgrids arises from its higher cost and implementation complexity. Model Predictive Control (MPC) offers excellent performance for industrial microgrids by enabling predictive optimization and coordinated management of energy resources, but its high computational demands limit its practicality for smaller, community-based systems. Distributed or Multi-Agent System (MAS) control provides high suitability for community microgrids, offering decentralized, fault-tolerant operation, while its moderate industrial suitability arises from coordination challenges in larger systems. Hierarchical control is very suitable for industrial microgrids due to its layered structure, which integrates primary, secondary, and tertiary controls for optimized performance, but it is only moderately suitable for community systems. Finally, hybrid control strategies combine multiple approaches to deliver optimal performance in industrial microgrids, though they are less practical for smaller community setups due to complexity and cost considerations.

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DISCUSSION

A microgrid comprises different types of DERs, with varying power outputs and availability factors. This can cause faster dynamics in operation as compared to large and centralized generations. An EMCS is thus very crucial for the stable operation of a microgrid. Microgrids range from small home and building-level MGs to large campus and district-level MGs. The various sizes of microgrids require different strategies to enable efficient and stable operation. Firstly, when considering EMCS structures, centralized systems are more suited to small-sized microgrids. This is because the communication lines are shorter, the number of DERs is small and thus requires lower computational capacity, and chances of expansion in the future are small. On the other hand, decentralized and distributed EMCS structures are more suited to medium/large-sized microgrids since they can better facilitate the system's expansion. Moreover, decentralized and distributed systems reduce the risk of cyber-attacks on a single EMCS point, thus reducing the risk of total system failure. This is an increasingly critical aspect to consider as systems become more interconnected. Secondly, network constraints must be considered when scheduling DERs in large microgrids due to the relatively wider spread of the power grid and the larger amount of electric power involved. However, this is not a pressing concern in smaller microgrids and can be disregarded to simplify the problem formulation.

The current review of real-time control methods shows that most of the methods are decentralized. This is perhaps because most control systems are implemented within the DERs. Moreover, while most of the research is done on AC systems, the trend in research on DC control systems is increasing. The study topics in microgrid control systems included improving performance under communication delays, providing a faster and more stable transient response, reducing control structure complexity for smoother and faster response, and managing BESS charge/discharge to minimize degradation. Also, numerous papers tested their proposed control methods on hardware setups and compared results with software simulation for better validation.

CONCLUSION

The need for grid expansion and renewable energy resources integration is inevitable and hence increasing around the globe due to the ever-growing population. This brings numerous challenges, including the need for considerable investments in transmission lines and issues related to cascading blackouts. In view of the mentioned issues, microgrids prove to be a promising alternative method of grid restructuring to cater to the future demand of grid expansion and transformation needs. However, due to the distributed nature of its resources, microgrids need complex energy management and control systems to operate in a stable and cost-effective manner. According to the literature researches, master-slave, peer- to-peer, and hierarchical architecture are considered as the most prominent control strategies in grid-connected or isolated MGs. Each control strategy proposes specific features to MG and MGC operation from the efficiency and reliability perspective. The analysis verifies that the hierarchical structure could provide more reliable operation by employing different control strategies such as centralized, decentralized, hybrid, and distributed control. Furthermore, planning and scheduling programs for MGs are investigated in order to determine the practical and technical specifications of the operating system. Therefore, an energy management system is essentially required not only to guarantee the optimal operation and economic feasibility but also to follow specific practical and technical considerations determined by planning and scheduling. Consequently, the optimum operation assessment of MGs is the main purpose of energy management system in MGs.

RECOMMENDATIONS

In the design and implementation of microgrid control strategies, several operational considerations are critical to ensure reliability, efficiency, and longevity of the system. This can be as follows:

- Islanding capability must be a central focus and rigorously tested, as the ability of a microgrid to disconnect from the main grid and operate autonomously constitutes one of its most essential features. This is particularly important for both industrial and community microgrids, where continuity of supply is crucial for critical processes or essential services.
- Battery Energy Storage Systems (BESS**)** play a key role in energy balancing and peak shaving; however, their degradation costs should be explicitly incorporated into the optimization and scheduling framework. By

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accounting for battery wear, control strategies can optimize charge–discharge cycles to prolong BESS life, protecting a major investment while maintaining operational reliability.

- Another important aspect is the robustness of control algorithms to communication **failures**. Microgrids often rely on centralized or distributed communication networks for coordination, and failures in these systems can jeopardize stability. Therefore, strategies must include fault-tolerant mechanisms to ensure system resilience and availability under partial communication outages.
- Additionally, renewable energy source (RES) output and electricity market price forecasts should be updated at short intervals, typically 5–15 minutes, enabling more accurate real-time energy management and cost-effective operation. Finally, for microgrids operating in islanded mode,
- the integration of fuel-based generators is recommended to provide emergency backup during periods of low renewable generation or unexpected contingencies. By addressing these considerations, control strategies can achieve a balance between performance, reliability, and economic efficiency in both industrial and community microgrids.

FUTURE RESEARCH STRATEGIES

Despite significant advances in microgrid control and energy management, several areas remain open for further investigation to improve reliability, efficiency, and scalability. One major research avenue is the integration of advanced predictive algorithms, such as artificial intelligence (AI) and machine learning (ML), into energy management systems. These approaches can enhance short-term forecasting of renewable energy sources (RES) and market prices, reduce uncertainty, and enable more precise scheduling of distributed generation and storage resources.
Battery Energy Storage System (BESS) optimization is another critical area. While current strategies often consider operational efficiency, further research is needed on lifecycle-aware optimization, which accounts for degradation costs, temperature effects, and aging models to extend battery lifetime while minimizing operational expenses.
Islanding and resilience under fault conditions also require more attention. Future studies could focus on designing control strategies that maintain system stability during unexpected islanding events, extreme load fluctuations, or simultaneous generator failures. This includes the development of fault-tolerant, communication-resilient algorithms for both centralized and distributed control architectures.
Hybrid control strategies combining droop, VSM, MPC, and hierarchical layers warrant further exploration, especially in microgrids with high penetration of intermittent renewable sources. Investigating optimal coordination between these strategies can improve dynamic response, power-sharing accuracy, and economic performance.
Finally, the integration of microgrids with smart grids and demand response programs presents another research opportunity. Studying interactions between multiple microgrids, peer-to-peer energy trading, and market participation can inform strategies that optimize both local and system-wide objectives. Continued research in these areas will enhance the operational robustness, economic efficiency, and sustainability of both industrial and community microgrids.

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