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Conventional Control Strategies in Building Energy Management

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Abstract. Building energy management is a critical component of global efforts to address climate change and environmental sustainability. Buildings account for a significant portion of worldwide energy consumption, making effective energy management in this sector crucial for reducing electricity costs and mitigating greenhouse gas emissions. This review article provides a comprehensive overview of conventional control methods used in building energy management, drawing from the latest research published in international journals and conferences. The review critically examines various control strategies, including hierarchical control. It highlights the key features, configurations, advantages, and limitations of these different approaches. The article also identifies the main challenges and research gaps in existing building energy control methods. These include the efficient control of complex, non-linear, and uncertain building systems. To address these issues, the review explores future research directions focused on developing adaptive, robust, and non-linear control techniques. The guidelines and control strategies discussed in this work aim to support the achievement of sustainable development goals through the optimization of energy management in buildings. By presenting the state-of-the-art in this field, the review provides valuable insights to researchers, building managers, and policymakers working towards a more energy-efficient and environmentally-sustainable built environment.

1 Introduction

To meet growing global energy demands, industries continue to rapidly consume available resources [1]. The COVID-19 pandemic caused a decrease in world energy consumption by 5.9% in 2020 compared to 2019 due to lockdowns. This significantly impacted the electricity sector, with global consumption dropping by 3.8% in the first quarter of 2020 compared to the same period in 2019 [2]. However, demand for renewable energy sources grew by 1.5% in the first quarter of 2020, attributed to new wind and solar projects. The report notes that renewable energy sources are often given priority within the grid and are not subject to the same production adjustments as other sources, making them less vulnerable to the effects of reduced energy demand [1].

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Looking ahead, Exxon Mobil forecasts that green and nuclear energy will constitute 25% of global electricity consumption by 2040 [1]. This shift towards renewable energy sources is crucial, especially as buildings, which account for 30-45% of global energy use, are major energy consumers [3–5]. Building subsystems like HVAC systems consume the most energy [3–5], and efforts to improve energy efficiency in buildings focus on balancing operational needs with cost and environmental considerations [6], as energy efficiency is seen as a key solution to rising energy demands [7]. However, improving the efficiency of building subsystems is challenging due to complex operational requirements, dynamic energy needs, and comfort considerations [8]. Building Energy Management are being implemented to address these challenges, improving building performance, efficiency, and energy utilization by automating demand response, monitoring energy costs, detecting anomalies, and organizing energy usage data [9,10]. Research on Building Energy Management applications is expanding, with studies focusing on subsystems like HVAC [11,12] and whole building energy management [13,14]. Recent research has highlighted the importance of comfort and energy management in buildings [15], as pre-determined occupancy schedules often differ significantly from actual occupancy patterns, leading to energy waste [15].This focus on efficient energy management extends to the realm of microgrids (MGs), which are often powered by renewable energy sources like solar and wind [16].Control strategies are crucial for the successful operation of microgrids (MGs) due to the intermittent nature of their distributed generators (DGs) [16]. Proper control techniques are essential for seamless power transition, particularly during grid disconnection, ensuring stable voltage and frequency to maintain electricity supply to consumers [16]. The integration of numerous DGs presents challenges for system control, potentially leading to poor power quality, security, stability, and reliability [17].Effective control is vital for managing power sharing methods, especially during islanded mode operation, and for ensuring the stability of voltage source inverters (VSIs) [18]. Stability analysis requires careful consideration of frequency, voltage, and power quality, necessitating well-designed control schemes [19]. Recent research highlights the importance of reactive power compensation, power loss reduction, and spinning reserve for enhancing MG system reliability and positively impacting distribution networks [20]. And this paper will explore the different conventional control techniques used in Building Energy Management, focusing on their effectiveness in achieving user satisfaction and energy efficiency while minimizing costs and environmental impact. This review aims to address current limitations in Building Energy Management by providing a comprehensive analysis of control strategies for a more sustainable future, ultimately contributing to an optimal built environment. The key contributions of this review are:

- A detailed overview of conventional control strategies: This work provides a comprehensive analysis of conventional control strategies for building energy management, focusing on their potential to optimize the integration of renewable energy sources. It explores how different control strategies can be used to effectively manage the intermittency and variability of renewable energy sources, such as solar and wind power, while ensuring reliable and efficient building operation. This analysis identifies opportunities for developing novel control algorithms that enhance the utilization of renewable energy in buildings, contributing to a more sustainable energy future.

- Challenges and opportunities: This research investigates the practical challenges and limitations of implementing conventional control strategies in buildings with a significant reliance on renewable energy sources. It examines how factors like grid integration, energy storage, and demand response capabilities influence the effectiveness of different control strategies. This analysis highlights research areas for developing advanced control algorithms that address the unique challenges of integrating renewable energy sources into building systems, ultimately contributing to the development of more resilient and sustainable energy grids.

2 Conventional Control Techniques

2.1 Rule-Based Control (RBC)

Operating on predefined "IF-THEN" rules, rule-based control (RBC) offers a simple and widely used approach in commercial building automation systems [21], employed for tasks like peak demand reduction. For example, RBC has been utilized in a quick chiller demand response approach to reduce building demand by up to 66% with minimal impact on occupant comfort [22]. Additionally, RBC is used for electric vehicle charging management in microgrids, leading to reduced energy consumption [23]. However, its lack of adaptability can lead to higher energy costs compared to advanced methods like metaheuristic algorithms [24]. Studies comparing RBC with metaheuristic algorithms highlight the superior performance of the latter, with 10-20% cost reductions and improved comfort through intelligent pre-cooling in microgrid applications [25]. Similar findings regarding the cost implications of RBC have been reported in other research as well [26]. Despite this, RBC often performs better than having no control system and remains a viable option due to its ease of implementation [21].

2.2 Proportional-Integral-Derivative control (PID) Control

PID control operates by continuously adjusting the output based on the error between the desired setpoint and the actual process variable, using proportional, integral, and derivative actions to achieve stability and desired performance [27].As shown in Figure 1 [28]. In [29], a PID controller was successfully employed for voltage control in a standalone microgrid. Similarly, reference [30] utilized a PI controller within an energy management strategy to ensure DC bus voltage stability in a microgrid composed of fuel cells and solar power. Reference [31] showcases the use of PID to regulate the bidirectional DC/DC converter of a standalone microgrid, comparing its efficacy to an artificial neural network controller (ANNC). To enhance system stability, Reference [32]proposes using PID to manage buck/boost converters in renewable energy sources. Despite these successful applications, the key drawback of the PID controller is determining the optimal values for each system variation.

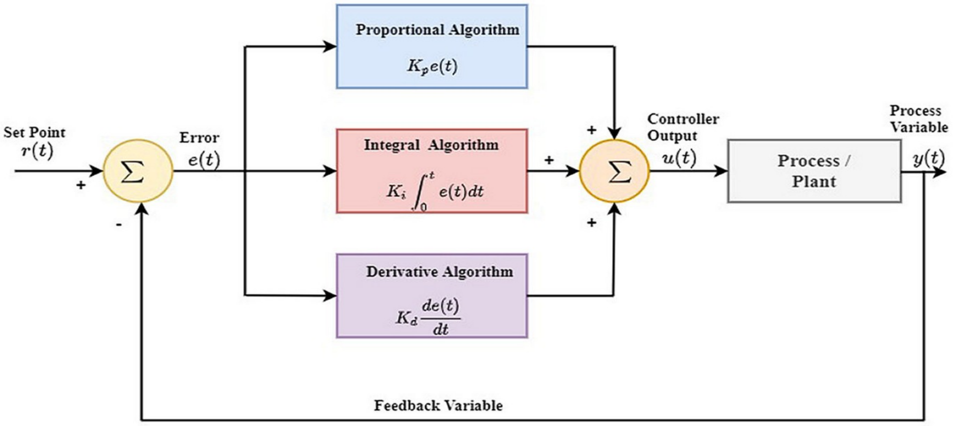

Fig. 1. Block diagram of process control using PID

2.3 Droop Control

Droop control is a decentralized strategy for managing active and reactive power output in parallel-connected converters without communication. By adjusting output based on frequency (for active power) and voltage deviations (for reactive power), it enables autonomous load sharing and efficient energy management in grid-connected mode. In islanded mode, it maintains voltage and frequency stability by allowing individual inverters to compensate for power imbalances. This approach eliminates communication needs, simplifies the system, and enhances overall reliability in both grid-connected and islanded scenarios [33–36]. Several droop control techniques have been suggested for linear load sharing in MGs [34,35,37,38]. Nevertheless, they are limited by their late transient response that needs a low-pass filter, imbalanced sharing of harmonic currents, and the intrinsic trade-off of voltage and power sharing [34,37]. A block diagram of the droop control strategy is shown in Figure 2 [33].

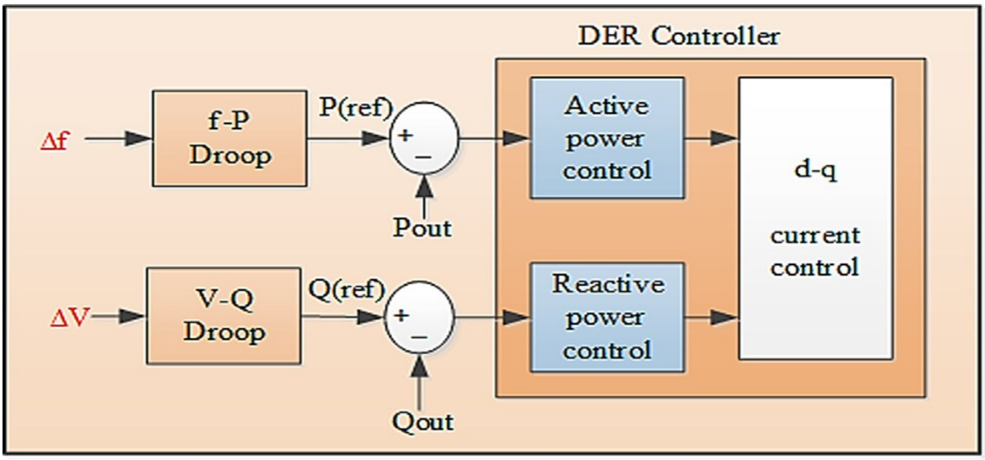

Fig. 2. Droop control strategy

2.4 Hierarchical Control

Hierarchical control in microgrids functions through a layered structure with primary, secondary, and tertiary levels, each playing a distinct role in ensuring stability and optimizing power flow [39,40] . The primary level focuses on maintaining local voltage and frequency stability through active and reactive power control [39,40]. The secondary level compensates for deviations and can implement various control architectures, such as centralized, decentralized, hybrid, or distributed, each with its own advantages and limitations depending on the scale and complexity of the microgrids community (MGC) [41–44]. Centralized control, suitable for smaller (MGC), faces challenges in data processing and is vulnerable to single-point failures [42]. Decentralized control allows individual microgrid optimization but may not guarantee overall system optimality [43]. Hybrid approaches attempt to combine the benefits of both but retain some drawbacks [44]. Distributed control, with its ability to distribute computational load and facilitate information sharing, has emerged as a promising solution for large-scale (MGC) [45]. Finally, the tertiary level focuses on optimizing power exchange with the main grid, considering factors like economic efficiency and overall system stability [39,40]. The integration of hierarchical control in a grid-connected individual MG is illustrated in Figure 3 [46].

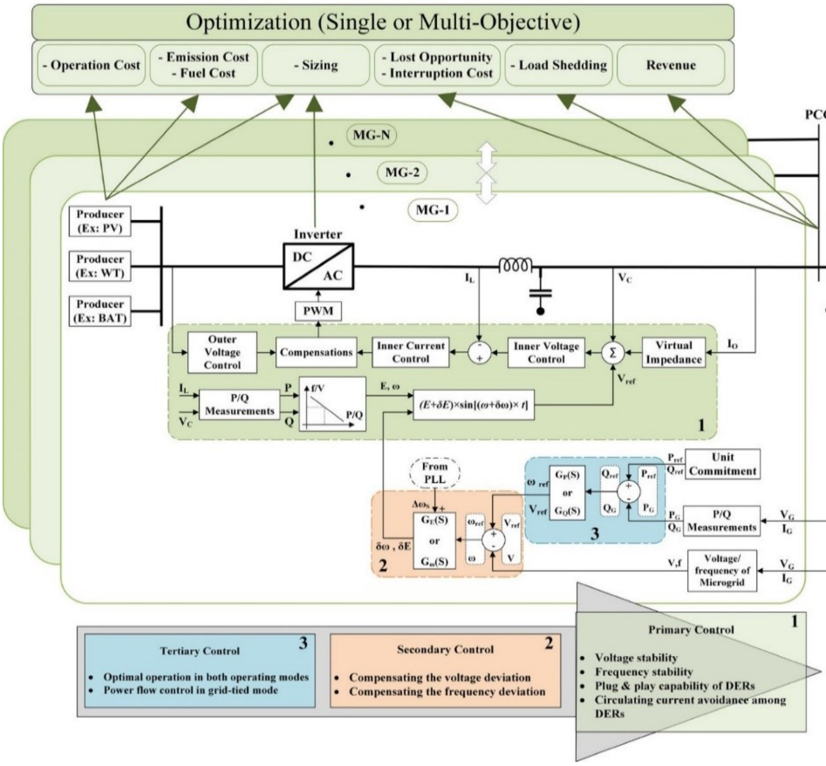

Fig. 3. Hierarchical control structure

2.5 Master-slave control

Master-slave control, a hierarchical architecture commonly employed in microgrids, operates on the principle of a designated master converter regulating the DC bus voltage while slave converters proportionally share the load based on the total demand [47] As illustrated in Figure 4 [46]. The master converter assumes the responsibility of maintaining voltage stability, acting as the central control entity, while the slaves respond to load changes and distribute power accordingly. However, this centralized approach introduces a vulnerability due to the reliance on a single master converter, creating a potential point of failure [48]. To enhance reliability and performance, researchers explore methods such as utilizing adaptable utility interfaces as control masters [48], implementing master-slave frameworks with advanced voltage estimation for efficient current sharing and communication robustness [49], employing distributed control schemes for voltage synchronization and optimal load sharing [50], and developing improved V/f control strategies with feed-forward compensation and robust feedback mechanisms for better dynamic response and resilience [51]. Additionally, mixed droop-V/f control facilitates seamless transitions between grid-connected and islanded modes [52]. These advancements aim to overcome the limitations of master-slave control and pave the way for more resilient, adaptable, and efficient microgrid systems.

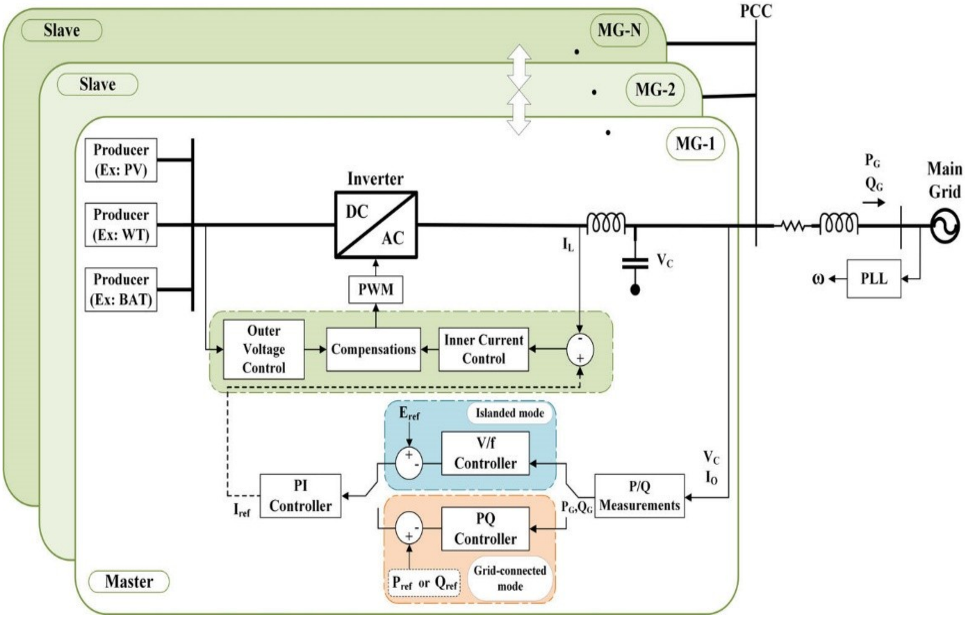

Fig. 4. Master-slave control structure

A comparative analysis of conventional control strategies for Sustainable Building Energy Management is presented in Table 1, based on a review of literature.

Table 1. Comparative of conventional control methods

Conventional Control strategies	Advantages	Disadvantages	Performance	Applicability
RBC Control	Simple, easy to implement, [21]	Inflexible, suboptimal performance, potentially higher costs [21,24].	Improved over no control [21].	Common in building automation, suitable for systems with basic control needs and predictable responses [21,22].

PID Control	Reliable and near-optimal performance in power systems [53].	Difficulty in determining optimal gain values for system variations [32].	Effective compared to alternatives like ANNC in DC/DC converter control within standalone micro-grids [31].	Diverse applications including voltage control [29], DC bus stability management [30], and more.
Droop Control	Simple, decentralized, no communication needed.[33–36]	Slow response, inaccurate power sharing, unbalanced harmonics.[34,37]	Acceptable stability for islanded systems but lacks precision. [34,35,37,38]	Islanded systems or limited communication, where precision is not crucial. [33–36]
Hierarchical Control	Effective control strategies ensure seamless transitions between operational modes, effectively addressing stability and optimization challenges in microgrids. [39,40]	Varying performance depends on the chosen control architecture, with centralized and decentralized approaches having limitations. [42,43]	A robust and adaptable framework is offered for managing complex microgrid systems, ensuring stability and enabling optimization. [39,40,44,45]	Complex microgrids, varying in scale and complexity, particularly those requiring seamless transitions and a balance between local and global optimization, pose a significant challenge. [39,40,44,45]
Master-slave control	Simple and efficient voltage regulation and load sharing in basic microgrids [47].	Single point of failure due to reliance on the master converter, making the system vulnerable to outages [48].	Outperformed by advanced control strategies in terms of resilience and adaptability to dynamic conditions and larger-scale microgrids [49–52].	Best suited for small-scale microgrids prioritizing simplicity and cost-effectiveness over resilience and adaptability [47].

3 Challenges And Future Directions

The main challenges associated with conventional control strategies can be summarized as follows:

- Inflexibility and Suboptimal Performance: RBC, PID, and Droop control methods often struggle to adapt to dynamic system changes, leading to suboptimal performance.
- Difficulty in Parameter Tuning: Determining optimal gain values for PID control and tuning fuzzy membership functions in PID-fuzzy controllers requires significant expertise and effort.
- Limited Scalability and Reliability: Hierarchical control systems face limitations with centralized and decentralized approaches, while master-slave control suffers from single point of failure vulnerabilities.
- Power Sharing and Harmonic Issues: Droop control exhibits slow response times, inaccurate power sharing, and unbalanced harmonics.

The review highlights the need for further research and development to address the challenges of existing control strategies. Here are some potential future directions:

- Improved Robustness and Reliability: Designing control systems that are less susceptible to noise, disturbances, and uncertainties.
- Enhanced Power Sharing and Harmonic Mitigation: Developing control strategies that ensure accurate and balanced power sharing while minimizing harmonic distortion.
- Decentralized Control: Exploring decentralized control architectures that are more resilient to failures and can handle large-scale systems.
- Adaptive Control: Developing control strategies that can adapt to changing system conditions and disturbances in real-time.

Conclusion

This review provides a comprehensive analysis of conventional controllers in Building Energy Management (BEM), highlighting their role in achieving sustainable development by emphasizing their importance in demand management, occupant satisfaction, cost optimization, and load shifting. The review examines the classification, characteristics, structure, advantages, and limitations of these controllers, identifying key barriers such as algorithmic complexity, deployment challenges, response time, and adaptive control. By critically evaluating existing schemes, the study could offer insights to researchers into the development and implementation of advanced controllers in the BEM, contributing to a more sustainable future. A follow-up to this work would be to complete it with a synthesis of intelligent control methods for building energy management and compare them with conventional methods.

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