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Energy management controllers: strategies, coordination, and applications

Mutiu Shola Bakare[1*], Abubakar Abdulkarim[1], Aliyu Nuhu Shuaibu[1] and Mundu Mustafa Muhamad[1]

*Correspondence:
shola.bakare@studwc.kiu.ac.ug

[1] Department of Electrical Engineering, Kampala International University, 20000 Ishaka, Uganda

Abstract

Energy management controllers (EMCs) are pivotal for optimizing energy consumption and ensuring operational efficiency across diverse systems. This review paper delves into the various control strategies utilized by energy management controllers and explores their coordination mechanisms. Additionally, it examines the architectures of energy management controllers and their real-world implementations. The paper surveys a spectrum of EMCs, including conventional-based, rule-based, optimization-based, hybrid methods, and commercial software-based approaches, highlighting their respective advantages and drawbacks. It investigates how these controllers are coordinated within complex energy systems to achieve optimal performance and adaptability. Furthermore, the review outlines different architectures of energy management controllers, ranging from centralized to decentralized designs, discussing their suitability for various applications and their impact on system performance. Real-world applications of energy management controllers in sectors such as smart grids, buildings, industrial processes, and transportation systems are examined. Case studies and examples demonstrate the efficacy of different control strategies and architectures in addressing specific energy management challenges and achieving desired outcomes. Overall, this review provides valuable insights into the current landscape of energy management controller design and implementation, offering direction for future research and development in the pursuit of energy optimization and sustainability.

Keywords: Energy management controllers, Control strategies, Coordination mechanisms, Architectures, Real-world applications, Energy optimization, Sustainability

Introduction

Modern power systems are changing. They now use more renewable energy sources (RESs), such as solar and wind power, as well as dynamic loads and batteries. This shift is turning traditional power systems into smart microgrids (MGs). These new systems offer technical and economic benefits, like reliability, cost-effectiveness, and reducing greenhouse gases. But to make sure everything runs smoothly, we need to monitor and control these complex systems (Ullah et al. 2023).

Energy management controllers (EMCs) have become increasingly important in recent years. With a focus on sustainable development and efficient energy use, research in this area has advanced alongside technological improvements. These controllers are all about optimizing energy consumption, improving efficiency, and integrating RES into the power grid. They are crucial for managing smart grids and MGs efficiently (Chen 2018).

Early EMSs focused on direct load control (DLC) architectures, which helped manage energy demand in residential areas with multiple buildings (Singh et al. 2023). More recently, stochastic optimization frameworks have been introduced. These frameworks use mathematics to minimize costs and optimize MG operation, taking into account factors such as seasonal load patterns and RES (Dagdougui et al. 2020).

To manage energy effectively, energy management (EM) programs are essential. They help monitor and control energy consumption patterns, minimizing waste and focusing on efficiency. Demand-side management (DSM) plays a crucial role in smart grids, allowing consumers to adjust their energy use based on incentives and electricity prices (Bakare et al. 2023). DSM techniques include peak clipping, load shifting, and demand response programs, all aimed at improving the sustainability and reliability of power grids (Hussain et al. 2018).

The evolution of energy management system (EMSs) has been influenced by advancements in hardware and software architectures, leading to standardized industry standards and sophisticated functionality. The field has evolved to improve energy efficiency, reduce costs, and address environmental concerns. Research on EMCs has evolved to address efficient energy utilization, renewable energy (RE) integration, and system optimization. Ongoing technological and research advancements continue to shape the field and drive innovation in EM practices.

The reviewed literature extensively explores EMC strategies across various domains, providing valuable insights into the complexities of controller selection and optimization for practical applications. Notably, Boodi et al. (2018) offers a comparative analysis of EMCs in buildings, focusing on white box, black box, and gray box models, while Lavanya et al. (2020) delves into EMC schemes for energy harvesting systems. Additionally, Roslan et al. (2019) reviews strategies for MG control, emphasizing the need for technological advancements to ensure sustainable operation in next-generation smart grid applications, with a particular focus on maximum power point tracking. Furthermore, Ahmad and Moubayed (2021a) provides a comprehensive overview of different control strategies for EM in buildings, including a prioritized indicator table for strategy selection.

Furthermore, research efforts such as Meng et al. (2016) and Elmouatamid et al. (2020) address the development of advanced MG supervisory controllers and EMS, highlighting the importance of predictive control and proposing future research directions. Ullah et al. (2023) presents an overview of EMC in hybrid MGs, assessing various control methods and their performance in voltage control, frequency stabilization, and energy saving. On a broader scale, Dong et al. (2022) reviews system controllers and proposes an implementation framework, CVEC-IEM, to guide efficient energy utilization and successful applications in hybrid electric vehicles (HEVs). The optimization progress for hybrid renewable energy systems (HRES) is also looked at in Thirunavukkarasu et al. (2023), which uses classical methods, AI, and hybrid algorithms to fix problems and make global solutions better.

Moreover, software tools for hybrid energy systems are extensively discussed in Sinha and Chandel (2014), highlighting their capabilities, limitations, and areas for further research. There is more information about control strategies for MGs in Feng et al. (2017), which talks about hierarchical and distributed structures and how they affect economic performance. Also, Kumar et al. (2019) goes into more detail about different control schemes, power management strategies, and future trends in hybrid energy storage systems (HESS) that use batteries and supercapacitors. Furthermore, Ahmad and Moubayed (2021b) describes a better hierarchized hybrid model predictive controller for buildings that focuses on multi-layered strategies. Minchala-Avila et al. (2015) goes over the best control methods for energy management and MG control and suggests future directions and perspectives for the best EMS. Lastly, Parvin et al. (2021) offers a thorough analysis of both traditional and intelligent control techniques for building energy management, offering insights into their classification, features, benefits, and drawbacks, with implications for sustainable development goals. Similarly, Xu et al. (2019) reviews EMC strategies in HEVs, analyzing rule-based and optimization-based approaches and highlighting future research directions and improvements.

The literature summary provides comprehensive insights into EMC across various domains, exploring diverse control methodologies and their practical implications, as shown in Table 1. Notably, overlapping capabilities highlight the complexity of controller selection for specific applications. Additionally, the review emphasizes the need for further research into optimizing hybrid RE systems. The study aims to address key research questions concerning common types of EMCs, the benefits and drawbacks of each controller type, common applications, emerging technologies, and implementation challenges. By addressing these questions, the current study seeks to elucidate new trends in EMC and their real-life implementation. The main contributions of this study lie in providing insights into emerging EMC trends and their practical applications, as summarized below:

- Comprehensive analysis of control methods and EMS approaches for MG development, offering insights into control architecture and integration strategies.
- Exploration of existing knowledge on MG control methods and EMS strategies in power system applications, highlighting challenges and issues in EMC.
- A detailed comparison and summation of recent control methods for MG systems, including hierarchical control structures, with the goal of achieving sustainable energy supply.
- A review of various EMCs, including classical, heuristic, and intelligent algorithms, along with an analysis of their applications and real-life implementations.

Control strategies in microgrid systems

Figure 1 outlines three main control strategies: hierarchical, decentralized, and centralized, each with its own advantages and challenges in managing MG systems.

Table 1 Summary of existing literature on EMCs

Challenges	Control strategy	Control coordination	EMC				Refs.
			Simulation	Implementation	Benefits and drawback	Commercial software	
	√	√	√				(Meng et al. 2016; Elmouatamid et al. 2020)
√			√		√		(Parvin et al. 2021; Xu et al. 2019)
			√				(Ullah et al. 2023; Lavanya et al. 2020; Ahmad and Moubayed 2021b; Shareef et al. 2018; Behera and Dev Choudhury 2021)
	√		√				(Minchala-Avila et al. 2015)
	√	√					(Feng et al. 2017; Kumar et al. 2019)
	√						(Roslan et al. 2019; Ahmad and Moubayed 2021a)
√			√				(Boodi et al. 2018)
						√	(Sinha and Chandel 2014; Song et al. 2022; Upadhyay and Sharma 2014)
			√			√	(Thirunavukkarasu et al. 2023; Khan et al. 2022)
	√	√				√	(Chauhan and Saini 2014)
				√			(Dong et al. 2022; Bisschoff et al. 2018)
√	√	√	√	√	√	√	This study

Centralized control

A centralized control system is one in which a central controller (CC) collects data from various system entities and makes decisions based on a global perspective, enabling efficient grid operation (Elmouatamid et al. 2020). However, this approach relies heavily on a single unit for system management, which can pose scalability and reliability challenges (Pourbabak et al. 2019). The CC delivers strong controllability and real-time observability of the whole MG system, using high-performance computation and secure communication infrastructure (Sahoo et al. 2017). However, it carries a heavy computational burden, risks system-wide operational disruptions, lacks scalability, and may not efficiently support plug-and-play functionalities. Additionally, the concentration of computational tasks and reliance on a single unit for voltage regulation limit system flexibility (Kumar et al. 2019; Cupelli et al. 2016).

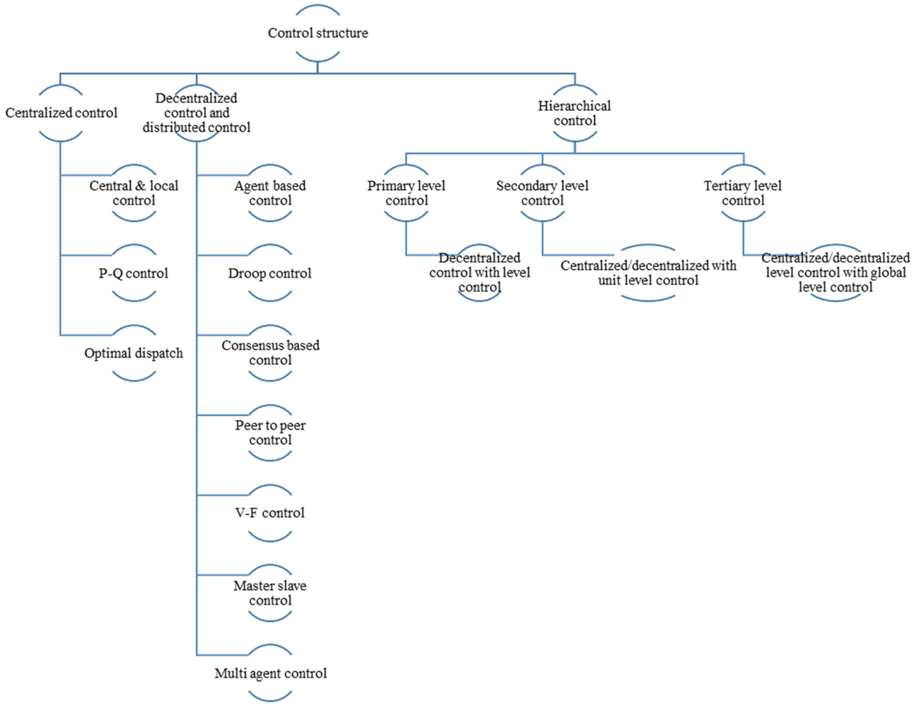

Fig. 1 Control strategies in microgrid systems

Numerous studies have explored centralized EM strategies, showcasing diverse approaches and methodologies. For instance, Lin et al. (2015) introduces a MG EM strategy integrating RE and battery storage systems, employing enhanced bee colony optimization (EBCO) for optimal scheduling dispatch. Similarly, Tsikalakis and Hatziargyriou (2011) discusses a central controller for MGs that optimizes interconnected operation by managing local DG production and power exchanges with the main grid. Moreover, Tabar and Abbasi (2019) investigates the impact of RES penetration and surplus power generation on electrical networks, presenting strategies to minimize renewable resource penetration and defects. Additionally, Guo et al. (2019) presents an optimal EM strategy for grid-connected photovoltaic MGs, emphasizing dynamic programming (DP) algorithms and grid I/O strategies. Furthermore, Nemati et al. (2018) introduces dispatch optimizers for centralized EMS, including real-coded genetic algorithms and MILP-based methods, which are tested under various operation policies. The literature also includes robust models for optimal MG energy management (Sardou et al. 2018), HESSs (Aktas et al. 2018), multi-objective LP models (Jaramillo and Weidlich 2016), and centralized control systems for island MGs (Almihat and Kahn 2023). Additionally, Li et al. (2017) proposes a combined sizing and EM methodology for MGs, while Dash and Bajpai (2015) introduces a power management strategy for HRESs, integrating PV arrays, fuel cell stacks, and batteries. Moreover, Elkazaz et al. (2020a) presents a novel EMS for MGs, while Helal et al. (2017) proposes an EMS for remote communities using a hybrid AC/DC MG.

Decentralized control

Decentralized control in the MG allows autonomous entities to manage subsystems independently, reducing computational complexity and enhancing system responsiveness. This approach leverages local measurements and peer-to-peer communication, promoting operational flexibility and fault tolerance (Pourbabak et al. 2019; Yamashita et al. 2020). The distributed processing system ensures greater reliability through redundant controllers and communication pathways, mitigating single-point failures. However, decentralized control faces challenges in global optimization and synchronization among distributed entities, such as limited information exchange, load dependency issues, and harmonics. Implementing distributed processing requires careful coordination and may introduce complexity compared to centralized approaches (Feng et al. 2017; Celik et al. 2017).

Numerous studies have explored decentralized EM strategies, showcasing diverse approaches and methodologies. For instance, the study in Zheng et al. (2018) used both deterministic constrained optimization and stochastic optimization to look at the unknowns in biomass-integrated MGs. This showed how cost-effective it is to combine a BCHP/PV system with battery storage. Also, Kuznetsova et al. (2015) looked at a MG EM framework that uses robust optimization (RO) and prediction intervals to deal with unknowns in wind power generation and consumption. They emphasized how important unknown events are for MG performance and reliability. Also, Ahmadi et al. (2022) showed a decentralized bi-level stochastic optimization method for multi-energy MGs. This method improved network flexibility and profitability by adding multi-energy storage systems and using the Latin Hypercube Sampling method to handle uncertainties.

A multi-agent decentralized EMS for autonomous polygeneration MGs, utilizing game theory to optimize energy management and control strategies among agents, is studied by Karavas et al. (2017). By employing Nash equilibrium, the system minimizes conflicting goals, offering operational and financial advantages over traditional distributed intelligence approaches in polygeneration MGs. The authors in Boglou et al. (2022) investigate the modernization of energy distribution grids, particularly MGs, to enhance electric power reliability. For efficient EV charging, a decentralized system using fuzzy cognitive maps and fuzzy logic controllers is proposed, resulting in an 8.8% reduction in investment costs over 20 years, a 31% increase in chargeable EVs, and reductions in peak load and load variances of 17% and 29%, respectively. This approach demonstrates significant benefits for islanding distribution grids with high EV penetration. Additionally, the integration of photovoltaic panels and EVs in residential grids is addressed, proposing a distributed optimal sizing strategy for small-scale PV systems that considers individual energy needs and EV charging, reducing energy costs by up to 40% and enabling distribution system operators to accommodate additional loads without network expansion (Boglou et al. 2023).

Similarly, Carli and Dotoli (2019) suggested a decentralized control system for scheduling electrical energy operations in smart home MGs, aiming to reduce grid energy supply by allowing users to exchange surplus renewable energy. Also, Du et al. (2022) proposed a variance-based optimization algorithm for decentralized HEMS. This algorithm achieves centralized performance without putting too much strain on computers and lowers the cost of system reinforcement and energy bills. The increasing demand for RES underscores the importance of decentralized models and stochastic methods in reducing operational costs and computational complexity (Faghiri et al. 2022). Additionally, Petrollese et al. (2016) introduced a new control strategy for managing MGs with high RES and energy storage systems, integrating optimal generation scheduling with model predictive control (MPC) for long-term optimization. Furthermore, Silani and Yazdanpanah (2018) proposed a method for energy management in MGs with stochastic loads, addressing the challenge of load uncertainty, and Yang et al. (2021) presented a blockchain-based VPP EM platform for residential users with RES, and flexible loads. Lastly, Wang et al. (2022) showed that decentralized power systems are possible and work well by creating a safe blockchain-based framework for managing and studying renewable hybrid MGs in multi-agent distributed structures. These studies collectively contribute to advancing decentralized EM strategies, offering innovative solutions to optimize MG operations and enhance RE integration.

Hierarchical control

Hierarchical control finds significance in smart grid systems due to their expansive geographical coverage and communication demands. Fully centralized approaches face coordination challenges among different local controllers (LCs), prompting the adoption of hierarchical control structures at primary, secondary, and tertiary levels (Molzahn et al. 2017). MG management encompasses technical, temporal, and physical aspects, necessitating a structured control scheme for effective operation. This paper suggests a standardized hierarchical control solution that is different from others because it focuses on coordinating multiple MGs and keeps EM functions out of secondary control (Meng et al. 2016).

Control structure

1. *Primary level*: The primary level is the first line of control in the MG, overseeing local power, voltage, and current control. It uses interface PCs to execute control actions based on upper-level setpoints. This level ensures immediate responses to local disturbances, maintaining voltage and frequency stability within acceptable limits. Typically, primary controllers employ droop control techniques to regulate power inverters, ensuring proportional power sharing and load balancing among distributed energy resources (DERs). The primary controller's primary objective is to maintain grid stability and reliability by swiftly addressing local disturbances and deviations from setpoints (Gaiceanu et al. 2020).
2. *Secondary level*: Positioned above the primary control, the secondary level assumes a supervisory role, managing power quality control within the MG. This level focuses on tasks such as voltage and frequency restoration, voltage unbalance correction, harmonic compensation, and power exchange with the main grid or other interconnected MGs. Secondary controllers gather system state information from primary controllers and other sources, making decisions to enhance MG performance and ensure compliance with grid codes and standards. Moreover, secondary control facilitates seamless integration of the MG with the main electrical network, enabling a smooth transition between islanded and grid-connected modes (Prabaharan 2018).

3. *Tertiary level*: At the highest hierarchical level, tertiary control introduces intelligence and optimization into the entire MG system. It aims to optimize MG operation based on various merits, primarily efficiency and economics. The tertiary controller utilizes advanced optimization algorithms and decision-making techniques to achieve optimal power flow, energy dispatch, and resource allocation within the MG (Guerrero et al. 2012). It leverages both MG-specific knowledge and external grid data obtained through information and communication technology systems. Economic dispatch, demand response coordination, energy trading, and grid support service provision. The tertiary controller optimizes MG operation by analyzing historical data and forecasting future load and generation patterns to minimize operating costs, reduce environmental impact, and enhance overall system performance (Elmouatamid et al. 2021). Tertiary and secondary control functions are integrated into MG supervisory control and EMSs. Control levels exhibit distinct bandwidths, simplifying modeling and analysis. As control levels ascend, regulation speed diminishes, with primary control responding within milliseconds, secondary control within seconds to minutes, and tertiary control executing discrete-time decision-making steps over seconds to hours. As shown in Table 2, the comparison between all the control strategies.

Several studies have advanced hierarchical EM strategies, demonstrating their effectiveness in optimizing decentralized energy systems. For example, Ghaffari and Askarzadeh (2020) proposes an efficient optimization approach for sizing hybrid power generation systems using RESs, highlighting the significant impact of RE penetration on total net present cost. Similarly, Sandgani and Sirouspour (2017) introduces a method for dispatching and sharing energy storage in grid-connected MGs, enabling cost-effective power transactions and reducing electricity costs through multi-objective optimization. Additionally, Aghdam et al. (2018) presents a contingency-based EM approach for distribution networks involving multiple MGs, preventing economic loss and benefiting both distribution networks and MGs. Furthermore, Elkazaz et al. (2020a) introduces a novel EMS for MGs, maximizing self-consumption of RESs and minimizing daily operating costs through convex optimization techniques.

Furthermore, Urias et al. (2014) proposes a recurrent neural network for optimizing the operation of electrical MGs, minimizing utility grid power, and maximizing RESs. Other studies focus on optimizing the individual objectives of stakeholders in MGs, employing robust optimization and non-dominated sorting genetic algorithm techniques (Kuznetsova et al. 2014). Additionally, Jin et al. (2017) and Zhang et al. (2018) describe hierarchical and stochastic MPC methods for integrated energy management in MGs, which achieve the lowest operation costs and lower forecasting uncertainties. Moreover, Han et al. (2019) provides an excellent design plan and hierarchical EM technique for island PV/hydrogen/battery hybrid DC MGs, validated through a hardware-in-loop platform and a real-time simulator. Finally, Choudar et al. (2015) discusses an EM strategy for grid-connected active PV systems, emphasizing local power flow management and stabilization techniques.

Table 2 Comparison between different control (Elmouatamid et al. 2020; Kumar et al. 2019; Sahoo et al. 2017; Cupelli, et al. 2016; Bakare et al. 2024)

Control strategy	Advantage	Disadvantage	Location	Example
Centralized	• The whole MG system has strong controllability and can be seen in real time • Suitable for small-scale MG systems with limited communication bandwidth • Enables optimal decision-making and simplifies EMC deployment • Utilizes high-performance computing and secure communication infrastructure • Ensures effective supervision and wide control coverage for efficient system maintenance	• System-wide operational disruptions from CC failures • Heavy computational burdens hinder deployment • Scalability limitations for plug-and-play functionalities • High connectivity and processing power requirements • Increased risk of failures and compromised reliability • Concerns regarding battery life and real-time communication effectiveness	Small size MGs or localized area	Master slave control
Decentralized	• Autonomous control capability in a distributed processing system • Enhanced reliability with peer-to-peer communication, reducing single-point failures • Independent control of distributed generators, boosting system flexibility • Improved privacy and minimized computational demands • Facilitates plug-and-play functionality with reduced complexity	• Limited visibility of the overall MG status and increased data transmission needs • Challenges in achieving global optimization and operating cost minimization • Implementation complexity relative to centralized and hierarchical control • Issues with load dependency, non-linear loads, and transient performance • Demand for effective synchronization and frequent reconfiguration	Battery storage system	Droop control
Hierarchical	• Suited for DC MG systems, facilitating local regulation of voltage and current by source converters • Enables variable voltage control between acceptable intervals and economical power dispatch among converters, MGs, and utility grids • Ensures synchronous generators maintain consistent frequency across the grid, enhancing controller coordination Efficiently dispatches operational constraints across different levels, reducing processing time • Combines previous control structures, facilitating optimal decision-making processes	• Distributed generators are tasked with voltage regulation and frequency control, adding complexity to operational coordination • Generators may operate in limited power mode, adhering strictly to electricity market plans rather than responding dynamically to grid needs • Accurate demand forecasting is essential for effectively planning generator output, requiring coordination between anticipated demand and actual load • Coordination between adjacent layers is necessary for seamless operation, necessitating efficient communication and synchronization • Communication faults in upper layers can disrupt information and energy transfer, potentially impacting system reliability • While there are fewer computational burdens, coordination challenges persist due to decentralized decision-making processes	Complex modern system	Agent based control

Energy management controllers

This paper categorizes EMCs into two main groups: those applied in real-life settings and those utilized in simulations. Figure 2 illustrates this. Real-life applications entail the practical implementation of EMCs in a variety of contexts. Conversely, simulation-based EMCs entail the use of these controllers in virtual environments to analyze their performance, optimize settings, and explore potential applications. By categorizing EMCs into these two domains, this research provides a comprehensive understanding of their functionalities, applications, and effectiveness in addressing EM challenges across different sectors and scenarios.

Simulation-based energy management controllers

Simulation-based EM encompasses a diverse range of methodologies, including commercial software-based solutions, conventional techniques, rule-based systems, optimization algorithms, artificial intelligence (AI) approaches, and hybrid methods. These simulation-based strategies are utilized to model, analyze, and optimize EM processes in various contexts, offering insights into system behavior, performance, and efficiency. By leveraging these different approaches, researchers and practitioners can simulate complex scenarios, evaluate different control strategies, and identify optimal solutions for EM challenges across different domains. This comprehensive exploration of simulation-based methodologies contributes to advancing the understanding and implementation of effective EM practices in diverse real-world applications.

Commercial software-based energy controllers

Commercial software applications are essential in energy management, offering functions like control strategies, simulation/technical analysis, economic optimization, and

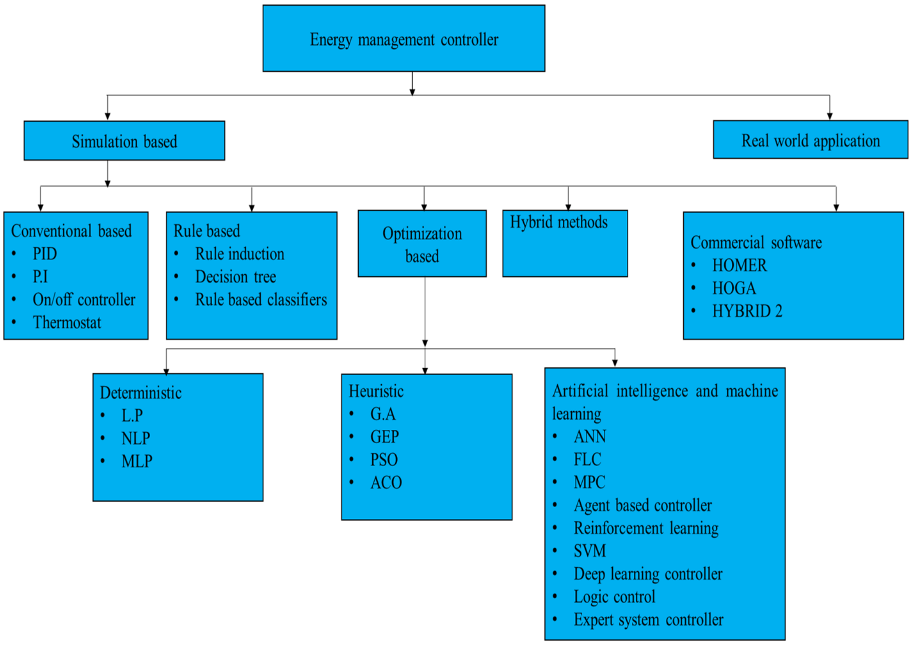

Fig. 2 Categories of energy management controller

multi-objective optimization. Commercial software-based controllers like HYBRIDS, HYBRID 2, INSEL, ARES, HOMER, iHOGA, RAP-sim, SOLSIM, TRNSYS, RETScreen, PROLOAD, WINSYS, DER-CAM, and SAM are particularly effective in optimizing energy systems (Sinha and Chandel 2014; Nallolla and Perumal 2022). However, only HOMER, HOGA, and HYBRID 2 have been established for control strategy implementation. Each has its strengths and disadvantages, and the choice depends on the specific project, as illustrated in Table 3. This paper explores various control strategy software, including HYBRIDS, HYBRID 2, and HOGA. Each piece of software has its own advantages and disadvantages, allowing researchers and practitioners to make informed decisions about its application in EM scenarios.

HOMER controller The Hybrid Optimization Model for Electric Renewables (HOMER) is a software developed by the National Renewable Energy Laboratory (NREL) that aids in the design and planning of HRESs. It is a user-friendly tool that allows for rapid feasibility assessments, optimizations, and sensitivity analyses across various system configurations. To simulate various system setups, the software uses the HDKR anisotropic model for solar photovoltaic systems and incorporates inputs such as technology options, component costs, resource availability, and manufacturer's data. With the ability to simulate a system for 8760 h annually, it provides comprehensive economic and technical comparisons and suggests load-serving policies with the most cost-effective energy source. HOMER requires six types of data for simulation and optimization (Bahramara et al. 2016). A schematic representation of HOMER can be seen in Mehta and Basak (2020). Although HOMER software is used in many studies, therefore, an article is needed that reviews studies utilizing the HOMER software for optimal planning and control of HRESs. One study (Zhang et al. 2022) focuses on proposing an optimal HRES for a medium-sized workshop in Ardabil, Iran. It integrates a wind turbine and a PV system, considering historical supply and demand data. The hourly-based simulations reveal that the optimal configuration consists of a 13 kW diesel generator, 1 kW PV array, 2 wind turbines, a 6.13 kW converter, and a 27 lead-acid battery storage bank, resulting in a minimum LCOE of 0.462 $/kWh. Another study Santos et al. (2021) introduces a methodology for sizing and operating MGs using HOMER Pro software. The MILP model-based strategy optimizes the day-ahead operation of a grid-connected MG, considering PV generation, battery storage, and energy transactions. The study by Jha et al. (2022) addresses the increasing demand for electric vehicles in southern Asian countries, proposing a 20 kW charging station utilizing biomass as a renewable resource. Efficiency studies with HOMER and MATLAB SIMULINK show cost savings compared to grid charging. Lastly, Ghanima and Nadir (2021) presents an experimental test of a standalone hybrid system in Constantine, Algeria, examining the MPPT charge controller's control strategy and demonstrating feasibility under various weather conditions.

HOMER's advantages include its user-friendly interface, powerful optimization capabilities, and ability to simulate complex energy systems. However, the major constraints of Homer are as follows (Sinha and Chandel 2014):

Table 3 Commercial based software tools (Sinha and Chandel 2014; Nallolla and Perumal 2022)

S/N.	Description	Control strategies	Simulation/technical analysis	Economic optimization	Multi objective optimization	Source	Advantage	Disadvantage
1	HYBRIDS		√			http://www.videohelp.com/software/Hyrid	HYBRID software provides a user-friendly platform for modeling HRESs, offering extensive modeling capabilities, long-term performance prediction, optimization features, and multi-objective optimization	HYBRID's user input parameter range and system parameter modification flexibility is limited, while its compatibility with Windows platforms beyond XP and complex control strategy pose a challenges
2	HYBRID 2	√	√			http://www.ceere.org/rerl/rerl_hybridpower.html	The interface, designed for user-friendliness, presents various electrical load options and furnishes detailed dispatching alternatives	While the project is well-documented, it encounters functionality issues on Windows platforms beyond Windows XP, with occasional simulation errors being reported
3	INSEL		√			http://www.insel.eu	INSEL provides a flexible system configuration platform, enabling detailed modeling of energy components and simulation capabilities for comprehensive system behavior analysis and testing	The software INSEL may face a learning curve, limited user input range, compatibility issues, and potentially limited support, potentially impacting its long-term viability
4	ARES		√			https://ares.en.download.it/	ARES software offers a user-friendly interface, comprehensive system analysis, and optimization capabilities for energy system modeling, enabling efficient and cost-effective system optimization	ARES may have limited features, a learning curve, compatibility issues, and limited support, impacting its adaptability to complex energy systems and changing technology needs
5	HOMER	√	√	√		http://www.homerenergy.com	The interface is user-friendly, providing an efficient graphical representation of results while accommodating hourly data with ease	The "Black Box" code was initially employed for first-degree linear equation-based models. However, it faced limitations in handling time series data, such as daily averages, which couldn't be imported effectively
6	iHOGA	√	√	√	√	https://ihoga.software.informer.com/2.3/	Leverage Genetic Algorithm and sensitivity analysis for the optimization of purchasing and selling energy options to the electrical grid within a net metering system, addressing both multi and mono objective scenarios	While the free EDU version offers valuable features, it is important to note its limitations in analysis capabilities and its reliance on an internet connection for license activation
7	RAP-sim		√			https://sourceforge.net/projects/rapsim/	Not reported	Not reported
8	SOLSIM		√			https://solsim.software.informer.com/	Not reported	Not reported

Table 3 (continued)

S/N.	Description	Control strategies	Simulation/technical analysis	Economic optimization	Multi objective optimization	Source	Advantage	Disadvantage
9	TRNSYS		✓			http://www.trnsys.com/	TRNSYS is a versatile simulation tool for energy systems, offering modularity, large component library, and integration capabilities for third-party models, making it widely used in research and industry applications	TRNSYS, a commercial software, has a steep learning curve, high costs, a less user-friendly graphical interface, limited 3D visualization capabilities, and may require frequent updates for bug fixes
10	RETSceen					http://www.retscreen.net/	The EXCEL-based software stands out for its robust product and meteorological database, primarily designed to excel in financial analysis	The system faces limitations such as the absence of time series data import options, restricted data input choices, and constrained capabilities in search, retrieval, and visualization features
11	PROLOAD		✓			https://proload.software.informer.com/5.4/	Not reported	Not reported
12	WINSYS					https://www.winsyslog.com/download/	Not reported	Not reported
13	DER-CAM			✓		https://gridintegration.lbl.gov/der-cam	DER-CAM offers a comprehensive economic analysis, integration of multiple technologies, customizable scenarios, decision support, and consideration of environmental factors for the efficient use of DERs	DER-CAM, a complex software for energy system modeling, requires accurate data input, may be challenging for beginners, may be less user-friendly, requires regular updates, and is resource-intensive
14	SAM		✓	✓		https://sam.nrel.gov/download.html	SAM is a user-friendly platform for analyzing RESs, providing a comprehensive analysis of performance and financial viability. It supports various technologies, financial modeling, scenario analysis, and integration of weather data	SAM, a user-friendly RE modeling tool, faces a learning curve, data requirements, and limited scope for advanced users due to its specialized nature, frequent updates, and limited scope
15	PVsyst		✓	✓	✓	https://www.pvsyst.com/download-pvsyst/	PVsyst is a comprehensive software for designing and optimizing solar power systems, offering accurate energy yield predictions, advanced shading analysis, financial analysis, realistic simulation, a comprehensive component database, tilt and orientation optimization, and a user-friendly interface	PVsyst is a commercial software with a learning curve, reliance on input data, and limited coverage of other energy systems, necessitating regular updates and maintenance
16	Energy plan		✓	✓	✓	https://www.energyplan.eu/download/	Not reported	Not reported

Table 3 (continued)

S/N.	Description	Control strategies	Simulation/ technical analysis	Economic optimization	Multi objective optimization	Source	Advantage	Disadvantage
17	LEAP		√	√	√	https://community.leap.com.au/s/downloads	LEAP is a comprehensive energy planning tool that integrates multiple energy sectors, enables scenario analysis, and supports emissions analysis, offering a user-friendly interface for efficient energy planning	LEAP, while featuring a user-friendly interface, poses challenges with a learning curve, data requirements, sensitivity to input data, complexity for detailed analysis, and limited integration with other tools

- HOMER's single objective function for minimizing NPC prevents multi-objective problems from being formulated, and it does not rank hybrid systems based on levelized energy cost.
- The Homer system's sensitivity inputs should consider the battery bank's depth of discharge, as it has a significant impact on its life and size.
- HOMER does not consider intra-hour variability.
- HOMER does not account for fluctuations in bus voltage.

iHOGA controller Developed for the simulation and optimization of hybrid renewable stand-alone systems, Improved Hybrid Optimization by Genetic Algorithms (iHOGA) is a powerful C++ program that accommodates electrical energy, hydrogen, and water loads. This versatile software can simulate systems of any size, connect to the AC grid, and define net metering and net billing cases. With features like multi-objective optimization, simulation in time steps, sensitivity analysis, and Monte Carlo simulation, iHOGA provides a comprehensive solution (Deshmane et al. 2020). Another notable creation from the University of Zaragoza, iHOGA, is designed specifically for the simulation and optimization of stand-alone hydrogen reactors. This C++ software excels at modeling systems with AC/DC electrical loads, hydrogen consumption, and water consumption. Offering optimization for various components like wind turbines, PV generators, hydroelectric turbines, batteries, auxiliary generators, inverters, chargers, and hydrogen components, iHOGA is capable of simulating and optimizing both grid-connected and standalone systems (Ganguly et al. 2017).

Setting itself apart from renowned software like HOMER, iHOGA boasts a detailed control strategy and unique features like calculating the Human Development Index and job creation factor. The software is exceptional in terms of multi-objective optimization, deeper technical–economic analysis, and more accurate models, making it advantageous in comparison to HOMER (Ganguly et al. 2017). A schematic representation of iHOGA can be seen in Saiprasad et al. (2019). However, it does come with some limitations, such as the inability to undertake probabilistic analysis and the usage of a more sophisticated control method owing to GA, which may provide issues for users to grasp (Carroquino et al. 2018; Bukar et al. 2019).

A Paris residence is being designed with a HRES that integrates wind, solar-photovoltaic, battery, and diesel-generator components. The system has been optimized to reduce CO2 emissions and unmet load by 57–73.8% compared to conventional systems (Shamachurn 2021). The study also explores component sizing in Portland, Victoria, Australia, using iHOGA software. In Tindouf, Algeria, a stand-alone PV system is evaluated for its techno-economic feasibility. The study uses iHOGA software to analyze total costs, CO2 emissions, and environmental impact, highlighting the potential of solar systems as a sustainable and competitive energy source. The research underscores the importance of selecting the optimal system configuration for HRES efficiency (Recioui et al. 2022).

The research explores RE applications in smaller communities using improved iHOGA PRO+ software. It uses a triple bottom line analysis to assess the techno-economic, environmental, and social aspects of RE systems. According to the study, achieving a minimum 70% RE penetration in the Aralvaimozhi community with the lowest HRES NPV is feasible. This approach can reduce CO_2 emissions and generate employment opportunities (Saiprasad et al. 2019). Another study compares iHOGA's performance with HOMER and iHOGA simulators, revealing a higher RE share (92% compared to 81%) and reduced CO_2 emissions. iHOGA also shows lower operating costs and electricity expenses, proving its efficiency and practicality in RESs (Hoarcă et al. 2023).

HYBRID 2 controller The Hybrid2 computer model, developed collaboratively by the University of Massachusetts and the National Renewable Energy Laboratory, stands out as a versatile and user-friendly tool for predicting the performance of hybrid power systems over the long term. This software encompasses a wide range of components and operating strategies, including AC and DC diesel generators, distribution systems, renewable power sources, energy storage, power converters, coupled diesel systems, dump loads, load management options, and supervisory control systems. Its graphical user interface, libraries, and control strategies facilitate the modeling of various hybrid systems, incorporating elements such as wind turbines, photovoltaic modules, diesel generators, battery storage, inverters, and connected loads (Manwell et al. 2006).

One of Hybrid2's notable strengths is its ability to assist designers in sizing and selecting operating options for hybrid power systems, taking performance and economic considerations into account, provided site conditions and load profiles are known. Despite its advantages in optimizing energy systems in remote areas, the software does have limitations (Colin and Boulanger 2000), considering factors such as resource availability, load demand, and system reliability. It does not provide guidance on system controls or voltage regulation, and users may need additional analytical tools for detailed system design. Furthermore, its restricted user input parameter range and inability to modify system parameters or operate on newer Windows platforms are noteworthy drawbacks (Kavadias and Triantafyllou 2021).

Chicago's RES, a hydrogen-based hybrid system, surpassed demand by 160% over a year without extra hydrogen or fossil fuel, utilizing solar, wind, fuel cells, electrolyzer, and compressor (Mills and Al-Hallaj 2004). This paper presents Genec's current state of modeling studies on photovoltaic hybrid systems, analyzes existing software options, and selects appropriate tools. HYBRID2 was used to simulate a hybrid system's operation and analyze the impact of specific parameters on system performance (Colin and Boulanger 2000).

Commercial software-based energy controllers such as HOMER, iHOGA, and HYBRID 2 provide valuable tools for engineers to optimize hybrid energy systems. Each controller offers its own unique algorithm advantages and limitations. By using these software tools, engineers can effectively design and analyze energy systems, considering factors like RE integration, grid interaction, and system reliability.

Conventional-based energy controllers

Conventional EM methodologies have long served as the cornerstone for optimizing energy consumption and cost reduction strategies in building systems (Technologies 2023). However, these methods often lack adaptability and real-time insights, hindering the timely identification of energy trends and performance evaluation. To address these challenges, recent studies have explored innovative control strategies to enhance EMSs (Godina et al. 2018). For example, (Hoffmann et al. 1984) presents a discrete-time self-tuning on–off controller with potential applications in industrial processes, while (Golob et al. 1992) introduces a self-tuning on–off control algorithm ensuring optimal system performance compared to conventional switching controllers. Moreover, Dong (2010) proposes an on–off controller for a PV pump, demonstrating its effectiveness in starting and stopping a water pump system in poor conditions.

Integration of advanced control algorithms, such as proportional-integral (PI) controllers, has shown promise in optimizing EMSs (Hoffmann et al. 1983; Cetin et al. 2019). These controllers have been applied across various industrial and residential applications, enhancing real-time processes and improving energy efficiency. Additionally, Erham et al. (2018) proposes a new optional controller for window A/C, offering enhanced accuracy and energy efficiency compared to conventional thermostat systems. PID controllers, which are widely used for temperature regulation and energy feeding scheduling, play a critical role in EMSs (Grant et al. 2022; Ciabattoni et al. 2012). They facilitate precise tuning to optimize energy costs, as emphasized by O'Dwyer (2006), and enhance system performance in residential grid-connected MGs with renewable hybrid generation (Pooja 2021). Similarly, a new PI controller for computing tiles in a system on a chip achieves superior performance with reduced frequency switches and enhanced energy savings (Caroline et al. 2016).

Practical implementations of innovative control solutions aim to improve energy efficiency across various domains. For instance, a control and energy monitoring system for dimmable LED lamp illumination utilizes a PID controller to adjust lamp luminosity levels based on natural light, thereby reducing electric energy consumption costs (Kumar et al. 2019). To address the challenges posed by the rapid fluctuations of wind and solar farms, a control schema for demand-side management employing a mathematical model and a simple PID controller is proposed (Yazdkhasti and Diduch 2019), offering reliable estimation and enabling fast response to dispatch commands. PID controllers extend to diverse domains, including HEVs and wireless sensor networks, showcasing their adaptability and effectiveness in optimizing energy systems (Saravanan and Sugumaran 2014; Le et al. 2012). These advancements underscore the pivotal role of advanced control systems in enhancing energy efficiency and sustainability across various applications.

Innovations in control technology continue to revolutionize energy management, with recent developments offering groundbreaking solutions for system-level power management (Holmbacka et al. 2011). By dynamically regulating processing elements in warehouse-sized data centers, the proposed power manager achieves remarkable energy savings, surpassing conventional methods (Molnos et al. 2015). Advances in energy storage systems, such as the proposed HESS, offer promising solutions for addressing the limitations of conventional batteries, thus shaping the future of electric vehicle technology (Bahri 2021). These pioneering control strategies underscore the critical role of advanced control systems in shaping the future of EM and sustainability.

Rule-based energy controllers

Rule-based methods have emerged as prominent tools in EMS due to their simplicity, real-time capability, and ease of implementation (Ostadian et al. 2020). These methods, characterized by sets of rules derived from engineers' expertise, offer interpretable solutions, contrasting with black-box models like neural networks (Ruddick et al. 2304; Ibrahim et al. 2021). Studies by Amayri and Ploix (2018) and (Morrison and Moore 2004) highlight the potential of these controllers to enhance energy efficiency, specifically noting a 6% increase over known optimal control techniques. Similarly, Yuan (2011) and Basma et al. (2018) explore the application of rule-based classifiers in energy management, demonstrating their effectiveness in decision-making guidance and optimal control for plug-in HEVs.

Innovations in energy system design and control methodologies further enhance EM efficiency. Liu et al. (2010) provides a new rule-based system design paradigm for power system automation and control, streamlining complex distributed generation systems and enabling direct modeling by operators within an optimal control framework. Similarly, Pippia et al. (2019) proposes a single-level rule-based MPC scheme for optimizing EM in grid-connected MGs, resulting in no performance loss and a significant reduction in computation time. Leveraging the Internet of Things, Peng et al. (2015) utilizes rule definition language in smart buildings to craft flexible rules based on high-resolution energy information, enhancing energy efficiency and smart device management.

Moreover, Bursill et al. (2020) introduces a rule extraction approach for MPC to enhance energy efficiency in buildings, resulting in significant energy savings in a real-world setting. In the industrial sector, the successful integration of rule-based EM and reporting systems optimizes operations by evaluating energy costs and environmental constraints (Bamber et al. 2005). Similarly, Abdul Basit et al. (2022) presents a rule-based algorithm for EM in smart homes, while Farrokhi et al. (2023) proposes a novel control strategy for HESS in DC MGs. Lastly, Hein et al. (2020) introduces an EM strategy for ship power systems, employing rule-based decisions to optimize generation and storage unit dispatching across different vessel types. These studies collectively underscore the pivotal role of rule-based systems in enhancing EM strategies across various domains.

Optimization-based energy controllers

In this section, the discussion revolves around the categorization of optimization-based EMCs into deterministic, heuristic, AI, and machine learning (ML) approaches, each possessing distinct advantages and disadvantages. Deterministic methods, rooted in mathematical optimization techniques, offer precise solutions but may struggle with real-world complexity and uncertainty. Heuristic AI methods, leveraging human-like decision-making processes, excel in handling complex environments but may lack optimality and scalability. Meanwhile, ML approaches, encompassing supervised, unsupervised, and reinforcement learning, exhibit adaptability and self-learning capabilities, yet may require extensive data and computational resources for training.

Deterministic-based energy controllers

Advanced control strategies are pivotal in optimizing EMSs across diverse applications. For instance, research efforts have focused on grid-connected MGs, aiming to maximize economic benefits by optimizing power flow and considering factors like battery operation costs and grid power profile shaping (Malysz et al. 2013). Similarly, a Lyapunov-based hybrid MPC has been introduced for RE-based MGs, ensuring closed-loop stability and recursive feasibility (Olama et al. 2018). Moreover, various control strategies for managed energy services using HEMs have demonstrated effective cost optimization capabilities (Wu et al. 2015). Additionally, LP methods have been explored for modeling industrial steam-condensing systems (Dragićević and Bojić 2009) and optimizing energy harvesting systems, showcasing the versatility of control strategies across different applications (Nkalo 2016). Furthermore, nonlinear control strategies for distributed generation in MGs (Shadaei and Samet 2020) and HESSs in EVs emphasize stability and optimization objectives (Fadil et al. 2020).

Addressing the complexity of building energy systems, advanced control methods such as MILP-MPC offer an intelligent real-time approach with significant cost savings potential (Bitner et al. 2023). Moreover, a proposed MILP-based distributed EM system for networked MGs utilizes iteratively adjusted price signals to ensure generation-load balance and maintain customer privacy, thereby promoting clean energy adoption (Liu et al. 2022). Moreover, various optimization methods, including dynamic programming and real-time implementable strategies, have been explored to minimize fuel usage and increase energy efficiency in passenger vehicles (Koot 2006).

Innovative EMSs leveraging advanced optimization techniques are crucial for promoting sustainable energy consumption and efficient operation. For example, a modular EMS for a grid-connected battery-based MG utilizes MILP to optimize energy scheduling, minimize operating costs, and enhance self-consumption (Luna et al. 2016). Similarly, optimization algorithms for fuel-optimal EM strategies in parallel hybrid electric powertrains demonstrate significant fuel consumption reduction potential (Robuschi et al. 2020). Moreover, MILP techniques have been explored in various contexts, addressing optimal power flow in electrical power systems (Wang et al. 2019), optimizing distributed energy systems, improving computational efficiency, and finding optimal solutions effectively (Yokoyama and Shinano 2016). Additionally, a mixed-integer quadratic programming method has been presented for efficient utilization of RES in island MGs, considering various factors to promote sustainable energy practices (Kumtepeli et al. 2019).

Heuristic controllers

Heuristic controllers have emerged as indispensable tools for optimizing EMSs across diverse sectors. Their efficacy in scheduling home appliances, managing renewable resources, and mitigating peak-to-average ratio challenges has been well documented. For instance, research has evaluated home EMCs utilizing genetic algorithms, binary particle swarm optimization (BPSO), and ant colony optimization, demonstrating their ability to reduce electricity bills and enhance user comfort (Rahim et al. 2016). In hybrid systems, meta-heuristic methods such as the sine cosine algorithm have been applied to control power flow effectively while minimizing hydrogen consumption (Çınar and Kandemir 2021). Moreover, the development of heuristic-based home EMCs aims to balance electricity bill minimization with user satisfaction maximization (Ahmed et al. 2018).

The study by Gopi and Reddy (2016) introduces a pattern search algorithm for automatic generation control in hybrid electric systems, outperforming benchmarks like Ant colony optimization and Ziegler-Nichols tuning. It demonstrates robust convergence, particularly under generation rate constraints and varying load scenarios. Daragmeh et al. (2022) proposes a framework for household energy consumption analysis, utilizing genetic algorithms (GA) and PSO for load scheduling, effectively minimizing electricity consumption and payments through dynamic pricing. Additionally, Rehman et al. (2018) evaluates an EMC's performance using meta-heuristic algorithms, focusing on electricity cost minimization and load shifting strategies. Meanwhile, Jasim et al. (2023) presents a heuristic-based EMC for residential buildings, aiming to reduce power costs, carbon emissions, and user comfort while lowering the peak-to-average ratio. Barua and Mohammad (2023) develops an optimization-based EMS for MGs, integrating renewable resources to optimize grid usage and reduce residential electricity bills.

In addressing the pressing need for sustainable EM solutions, heuristic optimization techniques play a pivotal role. GA, BPSO, and Wind Driven Optimization (WDO) have been utilized in HEMC systems to optimize energy consumption and reduce peak demand (Mahmood et al. 2023). Additionally, heuristic search algorithms like conventional PSO and advanced PSO enable the design of automatic generation control for isolated power systems, offering faster and less complex solutions compared to traditional methods (Patil et al. 2022). Furthermore, integrating harmony search algorithms, firefly algorithms, and enhanced differential evolution in EMCs aims at minimizing electricity costs and peak-to-average ratios while ensuring user comfort (Abideen 2018).

Evaluation studies validate the efficiency of heuristic-based home EM techniques, showcasing their effectiveness in reducing costs and achieving energy balance in smart grids (Rehman et al. 2016). Discussions on MG control emphasize the use of heuristic approaches to ensure reliable and economical energy use while maintaining power quality (Almada et al. 2016). Furthermore, integrating IoT and advanced communication technologies effectively addresses energy reallocation challenges in home EMSs (Hussain and Nardelli 2020). Simulation-based studies introduce efficient optimization algorithms for grid-connected energy hub plant management, contributing to profit maximization (Proietto et al. 2014). Additionally, the evaluation of home EMCs using GAs, enhanced differential evolution, and optimal stopping rules emphasizes their role in prolonging battery lifetime (Khan 2018) and reducing battery cycles in EMSs (Kefer et al. 2021).

AI and machine learning-based energy controllers

Various AI and ML techniques have been effectively employed in optimizing EMS, offering substantial benefits across residential, commercial, and hybrid energy domains. One notable approach, as exemplified by Ahmed et al. (2016), integrates ANN controllers within a home EMS modeled in Matlab/Simulink. This system reduces energy consumption by predicting optimal appliance ON/OFF statuses, without disrupting consumer lifestyles. Similarly, Revathi et al. (2022) explores ML-based smart energy managers for residential load management, showcasing successful integration with solar energy sources and EV technology, as demonstrated in Sulur village. These initiatives enhance grid system consistency and reduce peak power demands.

Furthermore, Zhou and Zheng (2020) presents a supervised ML method for building demand prediction, utilizing multiple linear regression, support vector regression, and backpropagation neural network techniques. This approach, enhanced with regularization techniques, significantly reduces grid import peak power. Additionally, Natsheh (2013) introduces an adaptive EMS for stand-alone hybrid power systems, demonstrating robustness and efficiency in power flow regulation through ANNs and FLCs.

In the realm of smart grids, Babu et al. (2023) proposes an intelligent EMS utilizing Deep Reinforcement Learning (DRL) algorithms to optimize energy consumption and production. This system aims to minimize costs while ensuring grid stability and reliability. Likewise, Nazeri et al. (2022) presents an integrated EMS for island MGs, employing a multi-step deep LSTM neural network and mixed-integer optimization algorithm to address frequency deviation issues.

Moreover, Intarungsee et al. (2022) suggests an AI-based approach to controlling IoT devices, effectively reducing electricity consumption and data variance. Fayyazi et al. (2023) introduces an intelligent EMS for conventional autonomous vehicles using reinforcement learning (RL), improving operational time. Ghosh (2023) proposes an improved MPC for EMSs, integrating the Emperor Penguin Optimization (EPO) algorithm and ANN with the MPC scheme to optimize power flow constraints, particularly with RESs.

Innovative applications include (Wijesingha et al. 2021) residential EMS, prioritizing loads, and leveraging rooftop solar to minimize grid dependency. Millo et al. (2023) delves into HEVs, employing deep learning models to design EMS that minimize CO2 emissions. Ramoul et al. (2018) introduces a neural network EMC tailored for HESSs, achieving substantial reductions in battery current.

Furthermore, Olaleye et al. (2023) and Ibrahim et al. (2023) focus on FLC-based EMSs for hybrid energy sources, emphasizing high energy security, cost optimization, and uninterrupted power supply. Lastly, Borioli et al. (2009) and Ananthu et al. (2022) explore the integration of AI techniques to enhance control room functions and improve the efficiency of PV energy generation systems. The integration of AI and ML techniques in EMS offers sustainable solutions to reduce electricity consumption and enhance system efficiency across various energy domains. These advancements hold promising potential for advancing the transition towards sustainable energy solutions.

Hybrid-based energy controllers

Various studies have explored the application of hybrid optimization controllers in EMSs. Bilbao et al. (2022) discusses the optimization of hybrid MGs, focusing on load sharing, energy storage, and integration into the electricity market. ML and ensemble methods are utilized to study MG optimization, indicating the potential for facilitating RE participation and integration. Jung et al. (2022) proposes the use of hybrid MPC for energy management in HEVs, demonstrating superior performance compared to traditional strategies. Additionally, Gheouany et al. (2023) presents an EMS that reduces electricity bills and peak-to-average ratios through load-shifting strategies based on dynamic pricing.

Furthermore, advancements in hybrid optimization controllers have been made in optimizing HESSs and EV energy management. Wang et al. (2021) focuses on optimizing the sizing of HES and EMS parameters using an adaptive MPC approach, resulting in improved system efficiency and battery lifespan. Kandaswamy et al. (2023) presents an efficient EM scheme for EVs using a HESS, demonstrating enhanced power flow optimization and battery performance. Using a hybrid optimization approach, the LAHBO method proposed by Vijayaragavan et al. (2023) optimizes electric vehicle home energy management, reducing costs and improving power factor.

Moreover, novel control approaches have been developed for optimizing power management in hybrid MGs. Lagouir et al. (2020) demonstrates a control strategy for effective power management, considering operating costs and pollutant emission levels, while Huang et al. (2020) proposes a hybrid optimization approach for residential demand response programs, demonstrating superior performance compared to existing methods.

Various studies have explored the use of AI and metaheuristic optimization techniques. Kumar et al. (2022) discusses the use of ANN hidden layers to predict sudden changes in home appliances and control appliances based on customer preferences. Natsheh (2013) presents an adaptive EMS for standalone hybrid power systems, employing ANNs and FLCs to manage power flow and load requirements. Additionally, Nesihath et al. (2022) utilizes PSO and the Honey Badger Algorithm to optimize DERs in MG systems, ensuring efficient and cost-effective energy generation.

Moreover, novel optimization algorithms such as the African Vulture Optimization Algorithm (AVOA) and Harmony Search Gray Wolf Optimization (HSGWO) have been proposed for enhancing the efficiency of hybrid RESs. Ghazi et al. (2022) employs the AVOA to improve the efficiency of PV and wind systems, demonstrating superior performance in terms of tracking speed and robustness. Nazeer et al. (2019) introduces the HSGWO technique for EM in smart homes, aiming to reduce electricity costs and maximize user comfort through a trade-off between cost and comfort.

Furthermore, hybrid optimization methods and intelligent real-time EM strategies have been developed for optimizing solar MPPT in HEVs and standalone hybrid power systems. Prasanna Moorthy et al. (2022) presents the WF2SLOA hybrid method for managing energy in HEVs, achieving superior torque split performance compared to existing methods. Reddy et al. (2022) proposes an optimized FLC for standalone hybrid power systems, demonstrating improved performance in minimizing loss of power supply probability (LPSP) and excess energy compared to PSO. Additionally, Hassanzadeh and Rahmani (2022) introduces an intelligent real-time EM strategy for plug-in HEVs, integrating battery life and fuel consumption optimization through DP and ANFIS modeling.

Application and implementation

The review encompasses a comprehensive exploration of diverse EMS strategies across various applications as shown in Table 4. Notably, the work by Chen et al. (2012) presents an EMS framework with FLC tailored for DC MG systems, emphasizing modeling and control through MATLAB/Simulink and integrated monitoring via LabVIEW. Further investigations by Shen and Khaligh (2016) delve into real-time EM strategies for EVs, showcasing significant reductions in battery peak current and state-of-health degradation. Additionally, Opila et al. (2013) introduces an EMC employing shortest path stochastic DP in vehicles, aiming to optimize fuel economy and powertrain activity. Despite hardware limitations, the controller demonstrates promising fuel economy results. Meanwhile, Bejaoui et al. (2020) focuses on implementing a hysteresis current controller for electric traction EM, effectively regulating output voltage through numerical simulation and experimental validation. Moreover, Marzougui et al. (2019) analyzes EM strategies for hybrid electric power systems, proposing fuzzy logic-based algorithms validated through real-time experimentation. Furthermore, Chojecki et al. (2020) discusses the implementation of an EMS in smart meters, showcasing significant reductions in energy consumption during peak demand periods, underscoring the potential of fuzzy logic algorithms for hardware implementation.

Notably, Andal and Jayapal (2022) emphasizes real-time control of hybrid energy systems utilizing the IoT, showcasing an innovative approach with wireless sensor networks for efficient power distribution. Furthermore, Elkholy et al. (2022) discusses power flow management in HRESs, demonstrating the potential for enhancing energy efficiency and reliability through real-time EMS implementations. Additionally, Boussetta et al. (2019) presents a real-time EMS for optimizing electricity distribution in hybrid MG systems, highlighting novel modeling methods and monitoring interfaces for practical applications. Moreover, Barnes et al. (2017) introduces a home energy and power management system that allows dynamic demand response through a mobile application, enabling users to regulate power usage effectively. Further, Krishnamoorthy et al. (2020) proposes an IoT-based method for monitoring power consumption, emphasizing efficient EM through automated data collection. Additionally, Zhang et al. (2021) presents a conceptual architecture for demand response management, offering guidelines for implementing multi-agent RL algorithms to optimize load control policies. Meanwhile, Marzband et al. (2016) introduces an EMS algorithm based on multi-layer ant colony optimization for MGs, showcasing significant improvements in system performance and energy cost reduction. Additionally, Padilla-Medina et al. (2020) presents an EMS for a residential DC MG, ensuring robustness and stability in energy distribution. Furthermore, proposes a smart HEMS utilizing solar panels and Bluetooth applications for load control, demonstrating cost-effectiveness and efficiency. Additionally, Qureshi, et al. (2017) introduces a HEMS utilizing real-time pricing information and user-defined priorities for load scheduling, highlighting its efficacy in optimizing energy consumption. Moreover, Buts (2023) presents a RE-based irrigation system with adaptive hybrid control, demonstrating its implementation and performance in LabVIEW. Additionally, Rangel et al. (2016) presents a real-time EMS optimization sequence for grid-connected MGs, showcasing its efficacy in managing power import constraints and fuel consumption. Furthermore, Nalina et al. (2023) proposes an embedded control approach for solar-wind hybrid systems, emphasizing the integration of novel DC-DC converters for efficient energy generation. Finally, Biswas et al. (2022) outlines the process of setting up a hardware-in-the-loop simulation platform for validating hybrid supervisory control strategies in HEVs, demonstrating real-time implementation and validation. Additionally, Okay et al. (2022) presents a prototype battery management system for grid-connected residential PV systems, ensuring safe operation and efficient energy management. This review collectively contributes to advancing EMC technologies across various domains, as shown in Table 5, highlighting the growing importance of real-time optimization and control mechanisms in enhancing energy efficiency and reliability.

Table 4 Application and implementation of energy controllers

Refs.	Component (s)	Workdone	Application	Limitation (s)
(Hoosain and Paul 2017)	• Arduino UNO with C-programming • Microcontroller • Radio frequency with wireless technology • Wireless smart power plug	The integration of wireless power plugs to control appliances during peak and off-peak periods in demand response systems and manual scheduling of power plug usage in DSM systems promotes energy efficiency and reduced monthly expenses	• Smart homes	The DSM system enhances the practicality of smart power plugs by allowing users to manually activate and deactivate times during peak hours
(Saeed et al. 2023)	• Al-Biruni earth radius optimization algorithm •SCADA-based monitoring an intuitive mobile app • PV panels • Battery • PLC • Analog input module • Smart meter •Inverter •AC loads • Motors •Lighting •Relays •Current sensors	They integrate demand response with a Time-of-Use pricing model, using the Al-Biruni Earth Radius optimization method. It also includes a theft detection device, load management, and SCADA solution for remote monitoring, potentially reducing electricity expenses by 48.45%	• Laboratory prototype	The paper advocates for the continuous use of advanced ML algorithms, dynamic load management strategies, energy storage solutions, cybersecurity measures, user participation, and environmental impact assessment
(Pawar 2019)	• SEM Gateway (Central controller) • Smart Socket Module (Appliance end) • Wireless ZigBee communication	A laboratory prototype for SEMS has been developed, demonstrating the effectiveness of power optimization algorithms through experiments. It uses wireless ZigBee communication and a self-diagnostic mechanism for reliable network formation. The prototype also features configurable priority settings for load categories, cost optimization algorithms for off-peak hours, and a secure web portal for energy management	• Laboratory prototype	limitations of the SEM Gateway and Smart Socket Module, encompassing network connectivity issues, challenges in managing multiple modules concurrently, compatibility concerns, and intricate installation procedures
(Panna et al. 2013)	• Microcontroller PIC18F458 • sensors • Actuators	Develop a smart home prototype utilizing a PIC18F458 microcontroller, along with sensors and actuators, to regulate lighting, air conditioning, and fans, enabling functions such as occupancy detection, temperature adjustment, fan activation, and light settings adaptation	• Smart home prototype	The SEM Gateway and Smart Socket Module face limitations in processing power and memory capacity, restricting their capacity to manage complex control algorithms
(Khakimova et al. 2017)	•PV panels •Solar collectors •Battery pack •Electrical heater •MPC •MILP •Sensors	They present a MPC scheme designed to manage the thermal and electrical subsystems of a small-sized smart house, aiming to minimize energy costs while maintaining room temperature	• Smart home prototype	The study's limitations include the quantization of battery state of charge, which can degrade the hybrid MPC scheme's performance. Future work should develop a non-quantized SoC estimator, run simulations over longer periods, and find reliable low-complexity approximations for the MILP

Table 4 (continued)

Refs.	Component (s)	Workdone	Application	Limitation (s)
(Mehta and Basak 2024)	• PLCs • Solar panels, • Wind turbines • Batteries • Inverters • Power conditioning units • Sensors	They introduce a hardware test-bench prototype utilizing Reconfigurable Allen-Bradley—Micro820/2080-LC20-20QBB PLC for robust control, energy management, and MG automation, evaluating the control algorithm's performance across diverse environmental conditions	• Smart home prototype	The PLC has relatively a limited processing power and memory capacity, which restrict its ability to handle complex control algorithms or large-scale MG systems
(Mubdir et al. 2016)	• Hidden Markov Model algorithm • WiFi and GSM technology • Home Smart Gateway • Sensing Units • End Appliance Unit	The study devised a Smart HEMS utilizing a Hidden Markov Model algorithm to discern residents' activity states and optimize home appliances accordingly, employing WiFi and GSM technology for data transmission, resulting in notable 18% energy savings	• 3 bedroom flat	The proposed algorithm can incorporate another feature to detect the security issues inside the home when the residents are away
(Velez-Varela et al. 2021)	• RFC-7460 • Green information technology • OID • SNMP	They developed a prototype tool capable of recording power consumption (PC) at the device level, leveraging internet protocol networks and supporting simple network management protocol and green information technology to collect energy-related data. This approach addresses gaps in information system management and establishes measurable metrics for behaviors in the energy conservation field	• Workstation	It is so complex to use
(Limpraptono, et al. 2021)	• Raspberry PI 3 PZEM-004t	They introduce a system for active energy efficiency, combining an electric power monitoring system with a smart panel to automate load control, record usage, and generate detailed reports, implemented through a prototype featuring a Raspberry PI 3 and PZEM-004t power energy meter, aimed at bolstering governmental initiatives in energy conservation	• Smart panel	The limitation of the system lies in its reliance on internet connectivity for data transmission, potentially leading to disruptions in monitoring and control functionality during network outages or downtimes

Table 5 Summary of energy management controllers: strategies, coordination, and applications

Control strategy	Controller	Simulation based				Prototyping	Advantage	Disadvantage
		Conventional based	Rule based	Optimization based	Commercial software			
Centralized	Hybrid2 (Colin and Boulanger 2000; Mills and Al-Hallaj 2004)				✓		User-friendly platform for models	User input parameter range and system parameter modification flexibility is limited
	GA (Rahim et al. 2016; Khan 2018)			✓			It can handle complex system and it is flexible to use	Lack of scalability and adaptability to diverse home EMSs with varying appliance configurations and user preferences
	CSA (Çınar and Kandemir 2021)			✓			It has fewer control settings and short execution time	Real-time implementation in large-scale hybrid systems is challenging due to the risk of prematurely falling into local optimum
	PSO (Mahmood et al. 2023; Nesihath et al. 2022)			✓			High computational efficiency, easy to use and fast convergence	Low memory and increase complexity
	AVOA (Ghazi et al. 2022)			✓			High performance and performance in EMC	Complexity in designing and tuning optimization algorithms
	DE (Khan 2018)			✓			It is suitable for global optimization problems	Premature convergence
	ON–OFF (Golob et al. 1992; Dong 2010; Hoffmann et al. 1983)	✓					Easy to use, reliable and cheap	Poor accuracy, limited range, No control over transient response, and limited applicability
	PID (Hoffmann et al. 1983; Cetin et al. 2019) (Grant et al. 2022; Ciabattoni et al. 2012)	✓					More accurate and precise than on–off controller	Expensive to design and implement
	Rule-based methods (Ciabattoni et al. 2012; Ruddick et al. 2304; Amayri and Ploix 2018; Morrison and Moore 2004; Yuan 2011; Basma et al. 2018; Liu et al. 2010; Pippia et al. 2019; Peng et al. 2015; Bursill et al. 2020; Bamber et al. 2005; Abdul Basit et al. 2022)		✓				low-cost alternative to mathematical algorithms	They are limited by poor hardware performance and may not always be the most effective approach
	LP (Dragićević and Bojić 2009; Nkalo 2016)			✓			They are strong in defining system stability and have a simple structure	It has limitations in handling nonlinear and dynamic systems
	NLP (Shadaei and Samet 2020; Fadil et al. 2020)			✓			They are functional over a wider operating range without retuning	Complexity in controller design and tuning may increase with system nonlinearity and dynamicity

Table 5 (continued)

Control strategy	Controller	Simulation based				Prototyping	Advantage	Disadvantage
		Conventional based	Rule based	Optimization based	Commercial software			
	MILP (Bitner et al. 2023; Liu et al. 2022; Koot 2006; Luna et al. 2016)			√			They offer powerful modeling capabilities and good solvers for EMC problems	High computational demands and complexity in formulating and solving mixed-integer nonlinear optimization problems
	FLC (Natsheh 2013; Olaleye et al. 2023; Ibrahim et al. 2023; Reddy et al. 2022)			√			Simplicity, safety, and high precision in EMC application	Complexity in designing and tuning fuzzy logic controllers for different system configurations and operating conditions
	FLC (Chen et al. 2012; Marzougui et al. 2019)					√	Simplicity, safety, and high precision in EMC application	Complexity in designing and tuning fuzzy logic controllers
	DP (Opila et al. 2013)					√	Ability to handle continuous change	Controller effectiveness is affected by unpredictable conditions
	RL (Zhang et al. 2021)					√	Flexibility and potential for adaptation to uncertain	Complexity in designing and tuning reinforcement learning algorithms
	ANN (Ahmed et al. 2016; Natsheh 2013; Ramoul et al. 2018; Kumar et al. 2022)			√			Ability to model complex and nonlinear functions, and high accuracy	Requires accurate modeling and training of ANN, may have limitations in adapting to dynamic household behavior and preferences
	RL (Babu et al. 2023; Millo et al. 2023)			√			Flexibility and potential for adaptation to uncertain	Requires extensive training and computational resources, may face challenges in defining reward functions and convergence in complex grid environments
	Supervised machine learning (Zhou and Zheng 2020; Bilbao et al. 2022)			√			Good performance and safety guarantee in controller synthesis	Face challenges in adapting to sudden changes and anomalies in demand patterns
Decentralized	iHOGA (Ganguly et al. 2017; Shamachurn 2021; Recioui et al. 2022)				√		Efficient problem-solving and good tracking performance	The analysis capabilities are limited and the system relies on an internet connection for license activation
	ON–OFF (Golob et al. 1992)	√					Easy to use, reliable and cheap	Poor accuracy, limited range, No control over transient response, and limited applicability
	GA (Daragmeh et al. 2022)			√			The robustness of GAs in nonlinear structures and constraints, making them suitable for real industrial environments	It is computationally expensive

Table 5 (continued)

Control strategy	Controller	Simulation based				Prototyping	Advantage	Disadvantage
		Conventional based	Rule based	Optimization based	Commercial software			
	PSO (Daragmeh et al. 2022)			√			Easy implementation, fast convergence, and good computational efficiency	Low memory and increase complexity
	ANN (Faraji et al. 2020; Eseye et al. 2019)			√			Ability to model complex and nonlinear functions, and high accuracy	Requires accurate modeling and training of ANN, may have limitations in adapting to dynamic household behavior and preferences
	RL (Eseye et al. 2019; Fang et al. 2021; Foruzan et al. 2018)			√			Flexibility and potential for adaptation to uncertain	Requires extensive training and computational resources, may face challenges in defining reward functions and convergence in complex grid environments
Hierarchical	Homer (Zhang et al. 2022; Santos et al. 2021; Jha et al. 2022)				√		Flexible and easy to use	Its complexity may pose a challenge for non-technical users
	MPC (Huang et al. 2023; Elkazaz et al. 2020b; Lefort et al. 2013)			√			Handling constraints and uncertainties, time-varying dynamics, and slow-moving processes with time delay	its complex algorithm that needs longer time than the other controller
	DP (Yang et al. 2022)			√			Ability to handle continuous change	Controller effectiveness is affected by unpredictable conditions
	PSO (Ren et al. 2022)			√			Easy implementation, fast convergence, and good computational efficiency	Low memory and increase complexity
	FLC (Jia and Zhao 2023)			√			Simplicity, safety, and high precision in EMC application	Complexity in designing and tuning fuzzy logic controllers

Conclusion

Energy management controllers (EMCs) play a crucial role in optimizing energy consumption and ensuring operational efficiency across a wide range of systems. This review paper has provided a comprehensive overview of various control strategies employed by EMCs, along with their coordination mechanisms and architectures. By surveying a spectrum of EMCs, including conventional-based, rule-based, optimization-based, hybrid methods, and commercial software-based approaches, we have highlighted their respective advantages and drawbacks.

This review has showcased the examination of real-world implementations, including sectors such as smart grids, buildings, industrial processes, and transportation systems, this review has showcased the diverse applications of EMCs. Case studies and examples have illustrated the efficacy of different control strategies and architectures in addressing specific energy management challenges and achieving desired outcomes.

Furthermore, our investigation into the coordination of EMCs within complex energy systems has shed light on the importance of achieving optimal performance and adaptability. We have outlined different architectures of EMCs, ranging from centralized to decentralized designs, and discussed their suitability for various applications and their impact on system performance.

Overall, this review provides valuable insights into the current landscape of EMC design and implementation. By offering direction for future research and development in the pursuit of energy optimization and sustainability, we hope to contribute to the advancement of EMCs and their role in shaping a more efficient and sustainable energy future.

Abbreviations

DLC	Direct load control
MG	Microgrid
DSM	Demand side management
EMS	Energy management system
HRES	Hybrid renewable energy systems
RE	Renewable energy
HEVs	Hybrid electric vehicles
HESS	Hybrid energy storage systems
EMC	Energy management control
CC	Central controller
EM	Energy management
EBCO	Enhanced bee colony optimization
RO	Robust Optimization
HEMS	Home energy management systems
VPP	Virtual power plant
LCs	Local controllers
DERs	Distributed energy resources
PI	Proportional-integral
AI	Artificial intelligence
ML	Machine learning
LP	Linear programming
MILP	Mixed-integer nonlinear programming
ACO	Ant colony optimization
GA	Genetic algorithm
PSO	Particle swarm optimization
BPSO	Binary particle swarm optimization
WDO	Wind driven optimization
HSA	Harmony search algorithm
ANN	Artificial neural network
DRL	Deep reinforcement learning
DP	Dynamic programming

RL	Reinforcement learning
DERs	Distributed energy resources
EPO	Emperor Penguin Optimization
MPC	Model Predictive Control
PV	Photovoltaic
ESS	Energy storage system

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