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# Energy Management System Strategies in Microgrids: A Review

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**Abstract:**
To accommodate the intricate nature of increasing energy demands, the conventional grid (CG) has been augmented with advanced communication technologies such as advanced metering with sensors, demand response, energy storage systems, and the integration of electric vehicles. To ensure localized energy balance and reliability, Microgrids (MG) have been proposed. Microgrids are low or medium-voltage distribution systems that operate with resilience, and regulate the exchange of power between the main grid, locally distributed generators (DGs), and consumers using intelligent energy management techniques. This paper provides a concise overview of MG, its operations, and a review of various energy management approaches. Within a MG control strategy, the energy management system (EMS) is the critical component responsible for balancing the available energy resources (CG, DG, ESS, and EVs) and loads, while contributing to the utility's profit. This article categorizes the methodologies utilized for EMS based on their structure, and control employed. Additionally, unexplored areas with potential for further research are identified.

**Keywords**: Microgrid, Energy management system, Renewable energy sources.

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## Introduction

In recent years, the global population has grown significantly, resulting in a substantial surge in energy consumption. This upsurge has led to the depletion of conventional energy resources such as coal, crude oil, and natural gas, with a concomitant increase in greenhouse gas emissions [1]. In response to these challenges, various countries have implemented policies aimed at introducing non-conventional and renewable energy sources to support electrification and transportation initiatives. In the field of electrification, the existing power grid-primarily relies on conventional energy sources for power generation, resulting in suboptimal power quality [2]. This low-quality power supply often leads to load shedding and blackouts, disrupting consumers' daily activities. Notably, the conventional grid employs one-third of the total generation fuel to produce electricity, with an associated eight per cent loss in transmission lines for the generated power [3]. Additionally, this electricity is used to meet peak demand, which has a five per cent probability of occurrence, with reduced reliability. Furthermore, conventional power generation fails to utilize the heat it produces for any other applications.

The limitations of the conventional grid may be overcome through the incorporation of local renewable energy sources or distributed generation (DG), which can reduce transmission losses and maximize output, including generated heat. However, the integration of dispatchable energy sources such as wind and photovoltaics (PV) poses a challenge due to their dependence on climatic and meteorological conditions, resulting in intermittent power generation [4,5]. Therefore, a hybrid energy system consisting of storage elements and renewable energy sources is utilized to ensure a continuous power supply. The future power grid must be intelligent to provide a reliable, cost-effective, and sustainable power supply to consumers. Adopting a smart grid can address the existing grid challenges by controlling the complex power exchange process and planning for the growing energy demand. The future grid must incorporate communication technologies and local MG to enable efficient system control [6,7]. Furthermore, integrating renewable energy resources at the load side necessitates a two-way flow of power and data, with the ability to adapt to management applications that leverage technology. The management of energy in MG involves the regulation of power supply to storage elements, demand response, and local controllers/local generation sources. A schematic representation of a standard MG structure is illustrated in Figure 1.

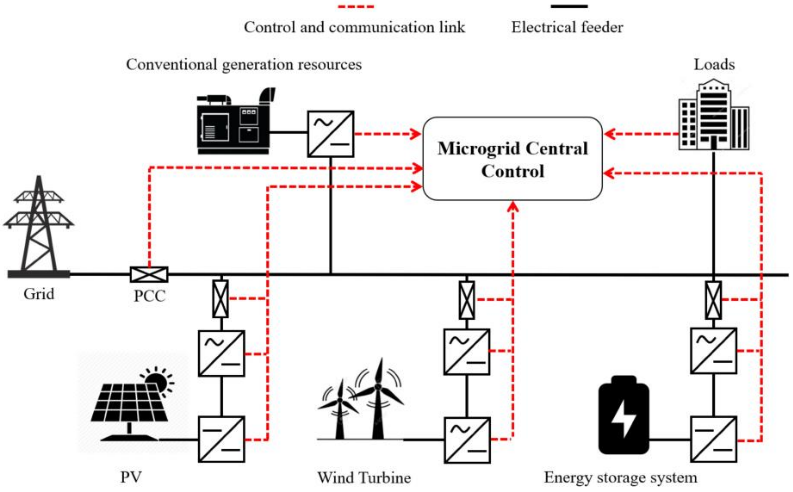

**Figure 1:** The schematic representation of a standard MG structure.

Recent research [8] has emphasized the significance of MG technology as a valuable supplement and effective utilization technique in the power industry. Despite the rapid development of this technology, MG still poses technical challenges. This article provides a comprehensive and systematic overview of key MG technologies, covering five aspects: typical structure, planning and design, operational control, protection technology, and power quality. Furthermore, this paper discusses the potential benefits and prospects of these key technologies. A different article [9] provides a comprehensive review of the latest control methods employed in AC MG that integrate DERs. This review examines hierarchical control techniques, management strategies, technical obstacles, and future trends in the system. Additionally, a comparative analysis of our proposed review with previous surveys of AC control techniques is presented, outlining their respective strengths and weaknesses. Furthermore, various significant features of the different power control methods applied in MG are compared and categorized, emphasizing potential benefits and diverse applications.

The article offers several contributions as follows: Firstly, it presents a succinct overview of the MG architecture, various classifications, and constituent components. Secondly, this paper reviews and critically assesses recent research on energy management strategies utilizing classical, heuristic, and intelligent algorithms. Each approach is thoroughly analyzed and its specific applications in energy management are examined. Thirdly, the study highlights important applications in energy management such as forecasting, demand response, data handling, and control structure. Lastly, the article provides valuable insights into the areas where research is still in its early stages and discusses potential avenues for future investigations in the field of energy management. The article outlines the energy management strategies proposed for MG, which are organized into the following sections: Section 1 introduces MG and energy management. Section 2 presents a brief overview of MG elements, architecture, classification, and communication. Section 3 provides an overview of different control structures in energy management. Section 4 presents the results and discussion. Finally, Section 5 concludes the article.

## Overview of Microgrid

Microgrids are small or medium-scale distribution systems that integrate various distributed energy resources, energy storage units, and smart control infrastructure to provide reliable and resilient power supply to end-users. The concept of MG has gained significant attention in recent years as a sustainable and efficient solution to address the challenges posed by centralized power systems, such as transmission losses, high costs, and vulnerability to outages.

### 1. Microgrid Components

A MG refers to a compact or moderate-scale distribution system equipped with intelligent infrastructure, which can effectively maintain equilibrium between demand and supply, while also providing security, autonomy, reliability, and resilience. The MG incorporates distributed generations (DGs), such as photovoltaics (PV), wind turbines (WT), micro-turbines (M-T), fuel cells (FC), and energy storage units (ESU), that are capable of supplying electricity without interference from the main grid. However, the high penetration of DGs may pose significant challenges to power system stability in large areas. Consequently, the concept of MG has been proposed to mitigate such risks. A MG typically comprises a small-scale low- or medium-level voltage distribution system, consisting of distributed energy resources (DERs), intermittent storage, communication, protection, and control units, that operate in coordination with each other to supply reliable electricity to end-users [10].

### 2. Distribution Generations (DGs)

In the realm of energy generation, conventional generation (CG) methods have historically been utilized to provide centralized electricity over long distances. These methods include coal-based thermal power plants, hydropower plants, wind-generation farms, and large-scale solar and nuclear power plants. In contrast, decentralized generation is defined as energy generated by end-users through the use of small-scale energy resources. When compared to conventional power systems, local generation substantially reduces transmission losses and the associated costs. Generation capacity can range from 1 kW to a few hundred MW, and these units are typically utilized to support peak load demand. Distributed generation sources encompass both renewable and non-renewable sources, such as wind generators, PV panels, small hydropower plants, and diesel generators. Combined heat and power (CHP) technology involves the integration of heating with electricity generation. CHP systems employ Stirling engines, internal combustion engines, and micro-turbines (M-T) that utilize biogas, hydrogen, and natural gas [24]. CHP technology stores excess energy and achieves optimal performance, leading to an efficiency of over 80%, as compared to about 35% for centralized power plants [11,12].

### 3. Energy Storage System (ESS)

Energy storage refers to devices that can store electrical energy in a storable form and convert it back to electricity when required. Different categories of energy storage technologies exist based on the form of stored energy, including mechanical energy storage (MES), thermal energy storage (TES), chemical energy storage (CES), and electrical energy storage (EES). The energy storage units are key components in MG energy management systems (EMS) that regulate supply and demand balance during distributed generation (DG) operations. Studies have shown that a MG system with multiple micro sources requires storage systems to maintain balance for intermittent sources in islanded mode. Commonly used energy storage devices in MG include batteries, flywheels, and supercapacitors, with batteries being the most cost-effective option despite their negative environmental impact. Fuel cells are also utilized in MG, using a chemical process to convert fuel into electricity, and hydrogen fuel cells are becoming increasingly popular due to their clean and safe operation [13,14].

## 4. Classifications of Microgrids

In general, a MG is connected to the grid at the point of common coupling (PCC) through a static transfer switch (STS), where the power grid manages voltage and frequency stability. In the event of a grid disturbance or failure, the MG maintains system stability by isolating itself from the main power grid and forming an islanded condition [15,16]. Renewable energy sources, such as solar, hydro, wind, and bioenergy, which are intermittent, are connected to the MG through power electronic converters (PECs) to ensure high-quality output power, providing a resilient, reliable, continuous, and efficient power supply. Based on the nature of the output obtained, MG is classified into AC source MG, DC source MG, and (AC/DC) hybrid MG [17,18]. An AC MG is a popular topology due to its flexible voltage level transmission using transformers. In an AC MG, an AC supply bus is introduced, and all distributed energy resources (DERs), either with DC or AC sources, are connected using PECs to AC loads. Since almost all loads in the power system are of AC nature, the AC MG is highly sought after. The structure of an AC MG is illustrated in Figure 2.

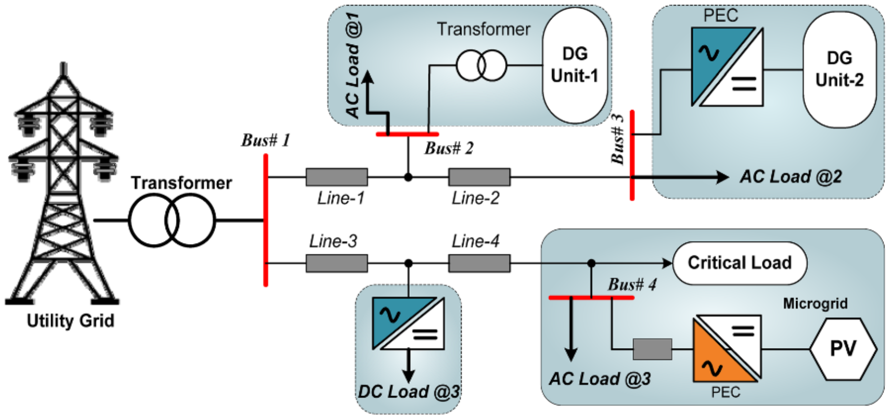

**Figure 2:** The structure of an AC MG.

The DC MG configuration comprises a DC bus that serves as a link for both AC and DC sources to transmit power to loads [19]. The rationale behind adopting a DC supply is to minimize the number of power electronic converters (PECs) required as DC sources are more readily available than AC sources. Moreover, the usage of DC supply eliminates the possibility of harmonics caused by PECs that are typically present in an AC supply [20]. The increasing demand for DC sources in portable devices, such as laptops and mobile phones, as well as for powering household appliances in remote areas, has led to the development of DC MG. A schematic representation of a typical DC MG structure is depicted in Figure 3.

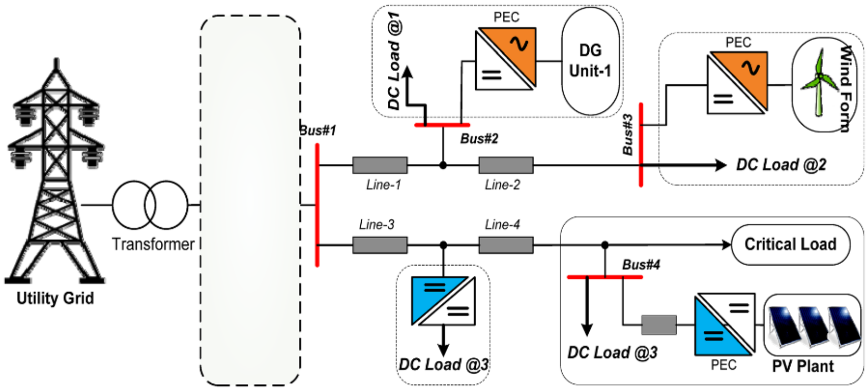

Figure 3: The schematic of a typical DC MG structure.

An AC/DC hybrid MG has been proposed to integrate both AC and DC sources and consumers into a single system. To implement this, AC sources and DC sources are connected to their respective buses where the outputs are directed to the consumers as required. The main objective of an AC/DC hybrid MG is to simultaneously use the supply from both DC and AC sources to minimize overall power consumption [21]. This can be achieved by the power electronic converters (PEC) installed at both supply buses that facilitate the bi-directional exchange of power between the source and load. A diagram of a hybrid MG is illustrated in Figure 4.

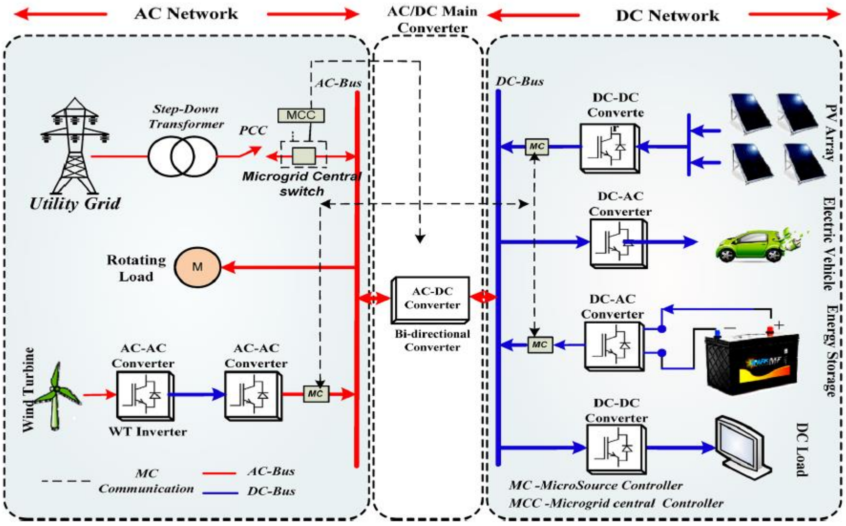

**Figure 4:** A diagram of a hybrid MG.

## Control Structure of a Microgrid

As a distributed power network on a small scale, a MG is subject to numerous variables and constraints requiring control. An energy management system is responsible for planning, overseeing, and regulating the MG's supply-demand balance to ensure dependable, cost-effective, and efficient operation [22,23]. This task involves addressing technical and economic considerations across various timescales and infrastructure levels, necessitating a control structure for managing the system's variables. The hierarchical control scheme has emerged as a widely adopted standardized solution, comprising three levels that operate with distinct operating times, data inputs, and control equipment. The primary level oversees the control of the distributed energy resource (DER) units, while the secondary level is responsible for voltage and frequency management in coordination with the primary level [24]. The tertiary level serves as the core control of the system, encompassing functions such as demand-supply management, storage management, renewable energy integration, power flow control, optimization of parameters, and control strategies, and is commonly referred to as the energy management system.

## Energy Management System Control Structure

As per the International Electro-Technical Commission's (IEC) standard application program concerning power systems, specifically IEC-61,970, an energy management system (EMS) is defined as a "computer system comprising a software platform providing fundamental support services and a set of applications providing the requisite functionality for the efficient operation of electrical generation and transmission facilities to guarantee adequate energy supply security while minimizing cost". The EMS performs various operations, including data analytics, forecasting, optimization, human-machine interface (HMI), and network reconfiguration, to enable real-time communication with the EMS [25].

As the geographical area of a power system expands, centralized control becomes challenging due to communication delays, resulting in delayed control responses. This approach is not only impractical but also uneconomical. Therefore, decentralized control is preferred, in which each unit has its local controller operating in an autonomous state, receiving voltage and frequency data [25]. Here, the local controllers exchange global information to make decisions for the overall system but do not share all information with other local controllers, allowing for prompt action in emergency situations. A third approach, distributed control, combines centralized and decentralized control schemes to provide control to both up to a certain degree [24]. In this scheme, each local controller unit utilizes local information, such as voltage and frequency, from neighbours to obtain a global solution through a two-way communication link with the central controller.

Forecasting is a crucial aspect of energy management, which can be categorized based on the duration of the forecast needed. These categories include: (i) very short-term (seconds to half an hour), utilized for the dynamic regulation of renewable energy sources as per the load requirements; (ii) short-term (half an hour to six hours), employed for energy planning amongst sources and storage devices; (iii) medium-term (six hours to one day), utilized for market pricing; and (iv) long-term (one day to one week), employed in load dispatch and maintenance [25].

The balance between generation and demand is a crucial constraint in the management of load. The problems associated with load demand balance can be categorized as supply-side and demand-side. Supply-side balance can be achieved through the use of a hierarchical control scheme for the economic scheduling of consumption by end-users [26]. Load control can be classified as either controllable loads, which are regulated based on price, or shift able loads, such as electric vehicle charging, washing machines, and dryers, which provide scheduling flexibility for demand response.

The demand-side balance necessitates careful evaluation by modeling renewable energy generation, specifically forecasting the supply to the system's users. Demand-side control is further sub-categorized into direct load control, or demand side management, and price-based load control, or demand response. The central controller oversees demand-side control through consumer agreements to mainstream economic agendas. In price-based load control, consumers are given the option to select their energy consumption based on the available market price [27].

## Result and Discussion

Energy management systems (EMSs) are essential components of MG, allowing for efficient and reliable operation. This review article discussed the different approaches to EMS in MG, including centralized, decentralized, and distributed control. Centralized control involves a single control center that manages the entire MG system. While this approach may be effective for small-scale systems, it becomes more challenging to manage larger systems due to communication delays. Decentralized control, on the other hand, allows each unit to have its own local controller, making it a more feasible and economical option for larger systems. Distributed control combines elements of both centralized and decentralized control, allowing for local controllers to communicate with each other and with a central controller to achieve a global solution. This approach provides a more flexible and adaptable system, making it a promising area for future research. The article also discussed the importance of load balancing in energy management, which can be achieved through supply-side and demand-side control. Supply-side balance can be obtained through economic scheduling and load control, while demand-side balance requires modeling and forecasting of renewable energy generation. Furthermore, the article reviewed the different applications of EMS in MG, including forecasting, demand response, data handling, and control structure. Forecasting is an essential component of EMS, and different forecasting techniques can be used for various periods, such as short-term, medium-term, and long-term. Demand response can also help balance the load and ensure efficient energy usage. Data handling is crucial for EMS, as it provides the necessary information for decision-making, while the control structure helps to ensure the reliable and efficient operation of the MG. Overall, the article provides valuable insights into the different approaches to EMS in MG and highlights areas for future research to improve the efficiency and reliability of these systems.

## Conclusion

This manuscript presents a comprehensive survey of recent developments in energy management strategies for MG, encompassing classical, heuristic, and intelligent algorithms. In addition, it provides an overview of MG architecture, various classifications, constituent components, communication technologies, implementation standards, and ancillary services essential for MG operations. Moreover, it highlights crucial energy management applications, including forecasting, demand response, data management, and control structure. Furthermore, the article offers an outlook on research frontiers and emerging domains that hold potential for advancing energy management practices. In conclusion, the implementation of an energy management system (EMS) is essential for the efficient and reliable operation of MGs. This article has presented an overview of different approaches for energy management in MGs, including centralized, decentralized, and distributed control schemes. The use of various forecasting techniques, demand response strategies, and load-balancing algorithms has been discussed. Classical, heuristic and intelligent algorithms have been reviewed to highlight the advantages and limitations of each approach. Communication technologies, standards, and auxiliary services required for the implementation of EMS in MGs have also been addressed. This article highlights the importance of selecting appropriate energy management approaches for MGs based on specific requirements and constraints. Further research is required to develop more efficient and effective energy management techniques that consider dynamic market pricing, renewable energy integration, and the reliability of the MGs system. With the rapid growth of MGs, the development of advanced energy management systems will be crucial for the sustainable and reliable operation of these systems.

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