EAI Endorsed Transactions
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State-of-the-art review on energy management systems, challenges and top trends of renewable energy based microgrids

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Abstract

Due to the increasing demand for electrical energy worldwide and environmental concerns, modern power systems are looking for a fundamental change. These changes include reducing dependence on the primary electricity grid and using renewable energy sources on a large scale. The emergence of microgrids in electrical energy systems will improve the level of these systems due to technical, economic, and environmental benefits. In this research work, the authors have conducted extensive studies on control methods, types of power sources, and the size of microgrids and analyzed them in tabular form. In addition, the review of communication technologies and standards in microgrids, as well as the review of microgrid energy management systems to optimize the efficiency of microgrids, is one of the main goals of the authors in this article. Also, in this article, the top 10 trends of microgrids in 2023 have been examined to increase the flexibility of network infrastructure, which helps readers to improve their strategic decisions by providing an overview of emerging technologies in the energy industry.

Keywords: Renewable energy resource; Microgrid; Energy storage systems; distributed energy source; Energy Management System

Received on 11 October 2023, accepted on 18 December 2023, published on 08 January 2024

doi: 10.4108/ew.4124

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1. Introduction

Today, electric energy consumers are looking for alternatives with higher reliability and quality at lower costs. They are also looking for solutions that can provide energy in a more environmentally sustainable way than other fossil fuel power plants. Distributed generation systems, in the form of microgrids, are the future of power generation, providing independent generation, integrated control, and environmental benefits at an affordable cost [1]. Microgrids are a promising potential for a modern power grid infrastructure [2, 3]. The new network control and monitoring field will develop network operation and provide a comprehensive infrastructure for network monitoring and control. This field can be considered a smart grid that, by monitoring all network parts, from production to distribution, suggests the most appropriate control solutions to possible network problems. In general, the progress of electricity networks can be mentioned under smart grids, and microgrids can be introduced as a key element in developing these networks [4, 5]. Since microgrids are usually on a smaller scale than more extensive networks, a significant improvement in control, management, and optimization will be created through smart and functional technologies. In this way, using microgrids as a part of smart grids and creating their optimal management systems can significantly improve power grids [6]. Microgrids are controllable and consist of a set of distributed products such as wind turbines, diesel generators, fuel cells, photovoltaic systems, energy storage, and load systems, and can be used in two forms of grid connection or islanding [7]. Microgrids have advantages such as CO2 reduction and environmental benefits use as a system for the simultaneous production of electricity and heat, the production of energy needed in geographical areas far from the reach of the national grid, the reduction of fuel costs due to the use of renewable energy sources for production, and the reduction of losses. In addition, they have disadvantages, such as Changes in electricity flow, increases in voltage and frequency fluctuations caused by renewable energy resources, widespread imbalance due to high single-phase loads, and permanent unavailability of renewable energy sources…In addition, addressing the limitations of microgrids such as establishing appropriate connection standards and strong protection systems, coordinating microgrids with the main grid after an event is a fundamental issue [8]. In Figure 1, the typical structure of a microgrid is shown. Microgrids are a small scale of low voltage power grids. According to the figure, it can be seen that the radial distribution network is connected to the power grid through an isolated device. In addition, distributed energy sources and loads can be controlled by the microgrid central controller. In addition, earthquakes, floods, and storms may cause widespread outages in the main power grids, in which case microgrids can safely supply the required electricity [9].

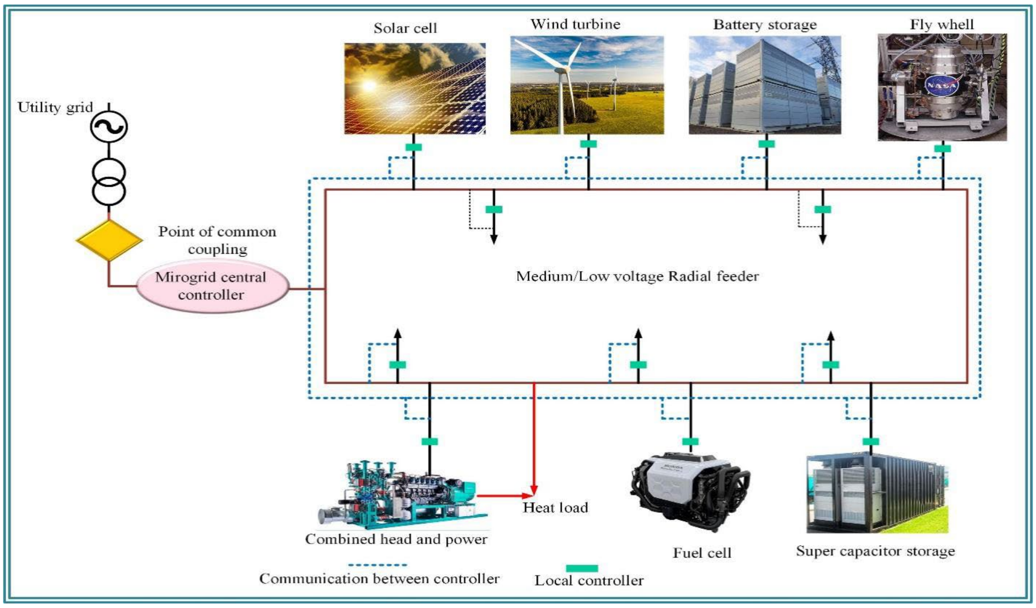

Figure 1. Typical schematic of a microgrid

As mentioned, microgrids include distributed generation units, energy storage systems, loads, and electrical devices that maximize the use of renewable energy sources to supply electricity to consumers and reduce dependence on external sources. Figure 2 shows the classification of energy storage systems and energy generation. In addition, in Table 1, a comparison of the different capabilities of different types of technologies has been discussed.

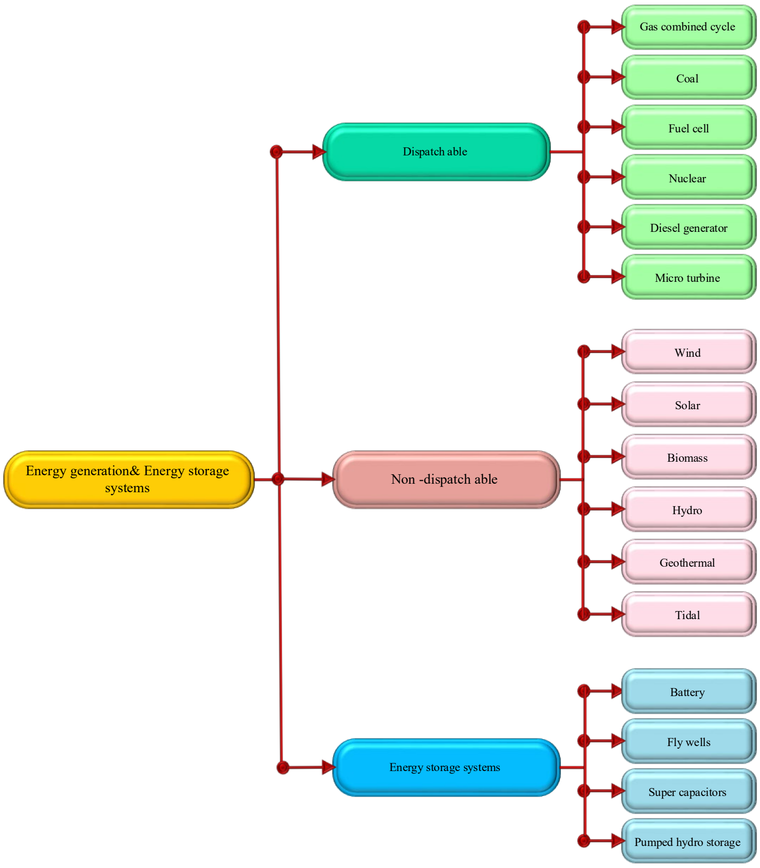

Figure 2. The classification of energy storage systems and energy generation

Table 1. Comparison of different characteristic of types distributed generations

Characteristic	Wind turbine	Solar cell	Fuel cell	Micro turbine	Gas turbine
Peak shaving	×	×	×	✓	✓
High reliability	×	×	✓	✓	✓
Economic fuel	✓	✓	×	×	×
Eco-friendly	✓	✓	×	×	×
Need to energy storage systems	✓	✓	×	×	×
Dispatch able	×	×	✓	✓	✓

In addition, the energy management of microgrids has become a hot research area, and in general, this system be designed in such a way that the dependence of the microgrid on the primary grid is reduced. In microgrids, loads are divided into controllable and uncontrollable categories. The first category includes loads with time flexibility, and their demand can be transferred to off-peak hours. Also, the second category comprises sensitive loads such as medical centers, which must be supplied with the required power at the time of demand. Sensitive and uncontrollable loads need more time flexibility, and transferring the demand to off-peak hours is impossible. In references [10-12], the authors provide a comprehensive review of microgrids, challenges, advantages, communication systems, and control methods. Also in reference [13] , the authors provide a comprehensive review on various technological developments related to microgrid system and a case study on the development of microgrid system using grid connection inverter. In addition, in the reference [14], the concept and classification of microgrids, control strategies and the important aspects of future microgrid research are outlined. In another review article, based on the research done, the optimal energy management of microgrids is analyzed [15]. In addition, in another research work, Cheng-Yu Yu et al ‹have simulated an AC microgrid integrated with distributed energy sources with the aim of improving its operation reliability through different

control strategies [16]. An overview of microgrid development, economic analysis and control strategy is presented in [17]. In [18], the authors have reviewed extensive research for the current progress in AC microgrid protection. In [19], Vahid Shahbazbegian et al, provide an in-depth analysis of various types of energy storage systems in multi-energy microgrids. Also, in another research work, the authors present an optimization model in which the energy requirements of thermal and electrical loads are supplied by using solar cells, wind turbines, thermal storage and battery storage [20]. Additionally in reference [21], the authors' main goal is to identify the common barriers and ultimate success factors in real-world microgrid implementation. In another research, many technical, political and regulatory challenges related to microgrid development have been addressed. If these challenges are faced, a sustainable energy system can be achieved [22]. Finally, in [23], various optimization algorithms have been analyzed with the aim of providing optimal solutions for the coordination of microgrid operators.
Organization of this paper are as follows:
In Section 2, the authors focus on the classification of microgrids in terms of size, controller and power supply, and the types of microgrid operation models. In section 3, the communication standards and requirements of microgrids are reviewed. In section 4, the energy management system of microgrids is discussed. Also, in Section 5, the authors review the top 10 microgrid trends. Finally, section 6 is dedicated to the conclusion of the article.

2. Classification and operating models of microgrids

In the 1990s, with the growth of distributed energy resources, the United States and Europe began to look for solutions to integrate large amounts of distributed energy resources into their grid infrastructure [24]. These solutions included modifying network infrastructure, improving control facilities, and establishing remote control centers in specific areas. This integration was developed and operated for the optimal use of distributed energy resources, reducing costs and optimizing the use of network infrastructure, as well as having a more stable energy system to reduce air pollution. The emergence of microgrids has happened due to the need for fast and stable communications in the electricity industry. In general, each micro-network must fulfill the following three conditions:
Ability to work in island conditions
Microgrids should be identifiable as a distinct subset of the distribution network
That it could operate on its own if disconnected from the macrogrid
During natural disasters, such as earthquakes, floods, and other events, the central power grid, as one of the critical parts of the infrastructure, becomes unstable and fails. Microgrids can act as a temporary backup source due to the prevention of external hazards and help the central power grid to avoid further hazards and destruction in these conditions [25] .According to Figure 2, in this section, the authors have conducted studies on various control methods, size and type of power supply.

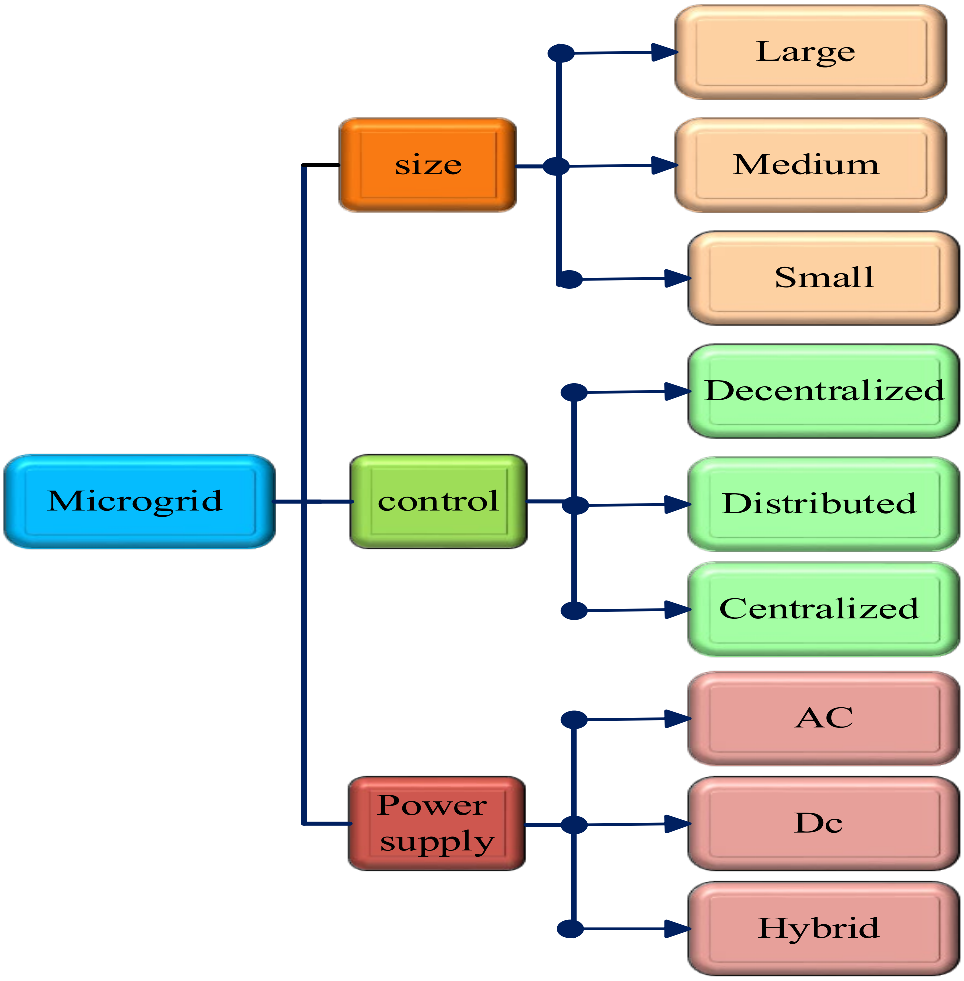

Figure 3. Classification of microgrids

2.1. Microgrid control approaches

Centralized control has only one controller that is in charge of managing all microgrid components. But the decentralized controller, unlike the centralized controller, has several controllers [10, 26]. In the distribution method, some information is shared among controllers so that each understands the behavior of others, improving the overall performance [27]. In Table 2, some main characteristics are compared in three centralized, decentralized and distributed control methods [28]. In addition, Table 3, mentions the advantages and disadvantages of three centralized, decentralized and distributed control methods [27].

Table.2. Comparison of five basic features in three centralized, decentralized and distributed control methods

characteristics	centralized	decentralized	distributed
Reliability	Low	High	Medium
Scalability	Low	High	Medium
The degree of complexity	High	Medium	Low
Degree of communication	High	Low	Medium
The degree of optimality of the solution	Globally optimized	Sub-optimal	Lack of optimality

Table .3. Advantages and disadvantages of centralized, decentralized and distributed control methods

Control method	Advantages	Disadvantages
Centralized	Globally optimized	Lack of communication infrastructure, Reduced scalability, Communication network affect stability
Decentralized	Very advanced scalability, very high reliability, no need for communication infrastructure in this control method, no computational complexity	Lack of optimality
Distributed	no computational complexity, Very advanced scalability, very high reliability	Lack of communication infrastructure, Sub-optimal solution, Communication grid affect stability

2.2. Types of microgrids according to the type of power source

In general, microgrids are divided into the following three categories in terms of dependence on the power supply [29-32]:
Ac
DC
Hybrid

2.2.1. AC microgrid

By definition, an AC microgrid is a typical microgrid system that is connected to an AC power source. It is worth mentioning that AC microgrids do not need additional control and are seamlessly integrated into current power systems. AC microgrids can be divided into the following three parts based on application [33-35]:
Single-phase
Grounded three-phase
Ungrounded three-phase
AC microgrids are the most common architecture among other options, such as DC microgrids or hybrid microgrids. AC microgrids are divided into the following three categories based on frequency [36-38]:
High-frequency
Low-frequency
Standard-frequency
High frequency AC microgrids operate at frequencies above 10 kHz. They are commonly used in applications such as electric vehicles. Also, low-frequency AC microgrids operate at frequencies higher than 50-60 HZ, and they are usually used in applications such as rural electrification and island microgrids. Finally, medium-frequency AC microgrids typically work at a frequency of 50-60 Hz and can generally be used in industrial and urban applications. In Figure 4, a typical AC microgrid is shown.

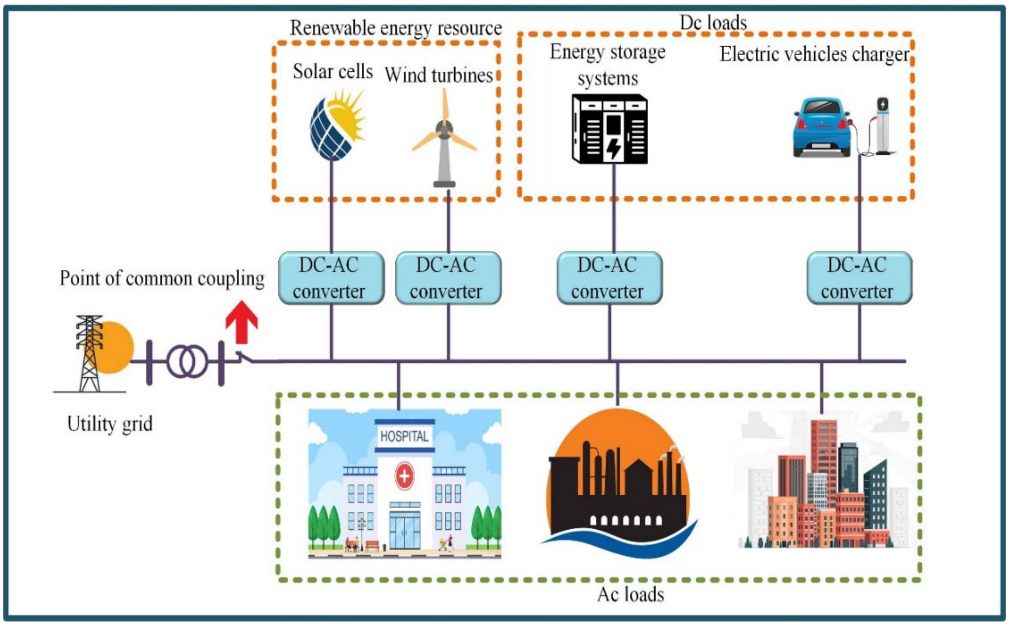

Figure 4. A simple model of an AC microgrid

2.2.2. DC microgrids

DC microgrids rely on DC electricity to distribute and store energy. It should be noted that these microgrids are designed to provide reliable power, often in remote or off-grid areas. Compared to AC microgrids, DC microgrids have advantages such as more use of renewable energy sources, high efficiency, etc. This model of microgrids can be designed for residential and commercial loads. For example, telecommunication, electric vehicles, and marine power systems are examples of commercial applications of DC microgrids [39, 40]. In addition, DC microgrids can be combined with energy storage systems and used when renewable energy sources are unavailable. Although DC microgrids can have many advantages, there are disadvantages, such as additional costs for these microgrids [41]. In Figure 5, a typical DC microgrid is shown.

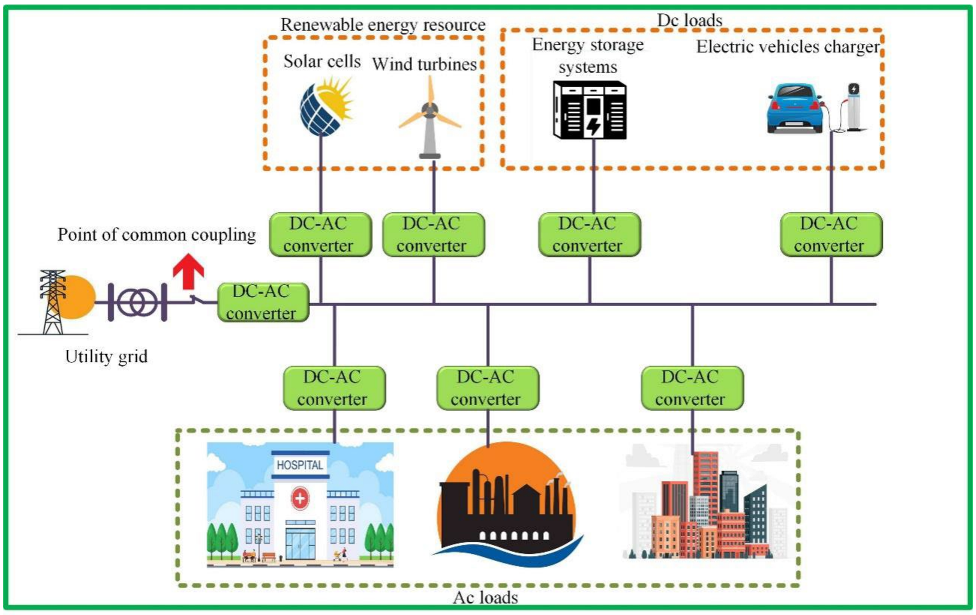

Figure 5. A simple model of an DC microgrid

2.2.3. Hybrid microgrids

Hybrid microgrids use renewable energy sources and fossil fuel generators to provide the required power [42, 43]. In addition, according to Figure 6, they can use energy storage systems, such as batteries. It is worth mentioning that energy storage systems are the main element of a hybrid microgrid. Energy storage can store grid power for times when the grid is limited or unstable. A combination of different energy sources such as renewable energy sources and fossil fuel generators in a hybrid microgrid will lead to increased flexibility and reliability. These networks can be used to meet special needs such as events. In Table 4, the general specifications of three microgrid models are summarized.

Table 4. Specifications of three types of microgrid

Micro grid type	Specifications
AC	- Presence of an AC bus to connect system components - Easy integration of AC microgrids into AC power systems - Using AC/DC converters as an interface between AC and DC system components [44-46]
DC	- Presence of an DC bus to connect system components - Using AC/DC converters as an interface between AC and DC system -The performance of AC and DC microgrids are similar -Because DC microgrids have no reactive power, their stability is better than AC microgrids -DC microgrids are the best option for integrating distributed energy sources [47-49] -They are divided into three opposite categories: bipolar, monopolar, and homopolar [50]
Hybrid	-Hybrid microgrids simultaneously benefit from all the advantages of AC and DC microgrids -The general structure of this type of microgrid is a combination of AC and DC microgrid -No coordination is required for production and storage units [51, 52]

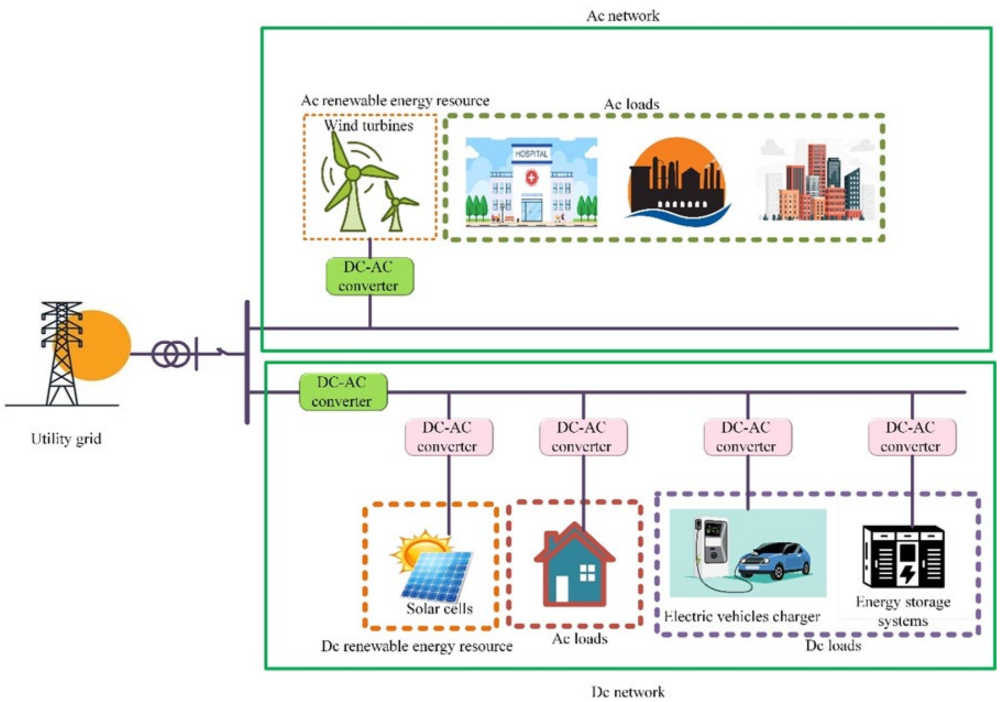

Figure 6. A simple model of an DC microgrid

2.2.4. Types of microgrids based on size

In general, microgrids in three scales, small, medium, and large, are examined using Institute of Electrical and Electronics Engineers (IEEE) test systems. Usually, small-scale microgrids are combined with renewable energy sources and diesel generators. Small-scale microgrids are a stable and reliable energy source with local control capabilities [53]. In addition to the ability to use renewable resources, small-scale microgrids also include energy storage technologies that provide improved performance, load control, and improved energy supply reliability. In medium and large-scale micro-grids, the fuel supply required is in addition to renewable energy sources based on oil or coal. Each of these three scales of micro-networks has a different application. For example, small-scale microgrids are suitable for feeding domestic loads and remote areas, but medium- and large-scale microgrids are ideal for supplying industrial and commercial loads. In Table 5, the characteristics of microgrids in three sizes, small, medium and large, have been examined [54, 55].

Table 5. Specifications related to the size of microgrids

Microgrid size	Fuel	Usage	Capacity	Market scale
Small	renewable energy sources	Home loads ,Island, Remote area, Small region power system	10MW	3000
Medium	renewable energy sources ,oil ,coal	Industrial &commercial loads	100MW	100
Large	renewable energy sources ,oil ,coal	Industrial &commercial loads	1000MW	10-20

2.3. operating models of microgrids

A microgrid is an independent electrical network capable of producing, storing, distributing, and consuming electricity. The microgrid can connect and exchange electricity with the primary grid through the point of common coupling to the grid and will be able to inject its electricity into the main grid and take electricity from the main grid if electricity is added[56]. Electricity is required. In this way, the balance between production and consumption of electricity can be maintained. But sometimes a fault in the main network may cause abnormal conditions at the common connection point of the microgrid, in which case the microgrid operates independently and is not connected to the main network. This means that all the electrical needs of the region are provided by the microgrid [57]. This situation occurs mostly in areas where access to electricity from the main grid is difficult or if the main grid is interrupted, the microgrid continues to supply electricity independently. For this purpose, the microgrid consists of a series of electricity generation equipment from renewable energies, water and heat, which are used to create an independent electricity network. Figure 7 shows the operational models of microgrids [58].

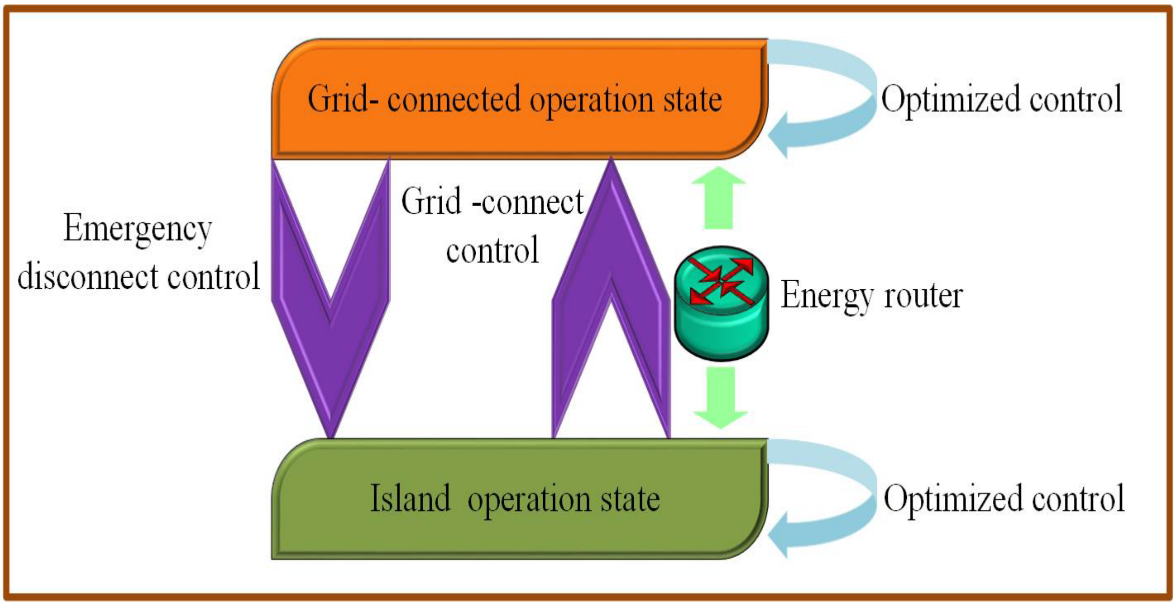

Figure 7. Operating models of microgrids

3. Communication requirements and standards in microgrids

Communication requirements and standards are essential for optimal operation and management of microgrids. All devices and systems in microgrids should be able to communicate with each other effectively, safely, and seamlessly. Some communication standards for microgrids are shown in Figure 8. In addition, the communication system architectures of a microgrid are divided into three basic parts [59, 60]:

Home Area Network (HAN)
Field Area Network (FAN)
Wide Area Network (WAN)

HAN networks are networks with low coverage and low bandwidth. These networks are mostly used in communication between microgrid assets. The three protocols WiFi, Zigbee and Bluetooth are the most common communication protoc ols in these networks [61, 62]. Also, the wide WAN network is responsible for the exchange of information between the micro-network and the bandwidth. In addition, it should be noted that FAN is responsible for transferring information between HAN and WAN layers [63]. Also, because the coverage range of this network can be in kilometers and its bandwidth can be tens Mbps, this layer is the most optimal mode for microgrid community applications compared to HAN and WAN cases [64]. In Table 5, the specifications of three communication systems are listed.

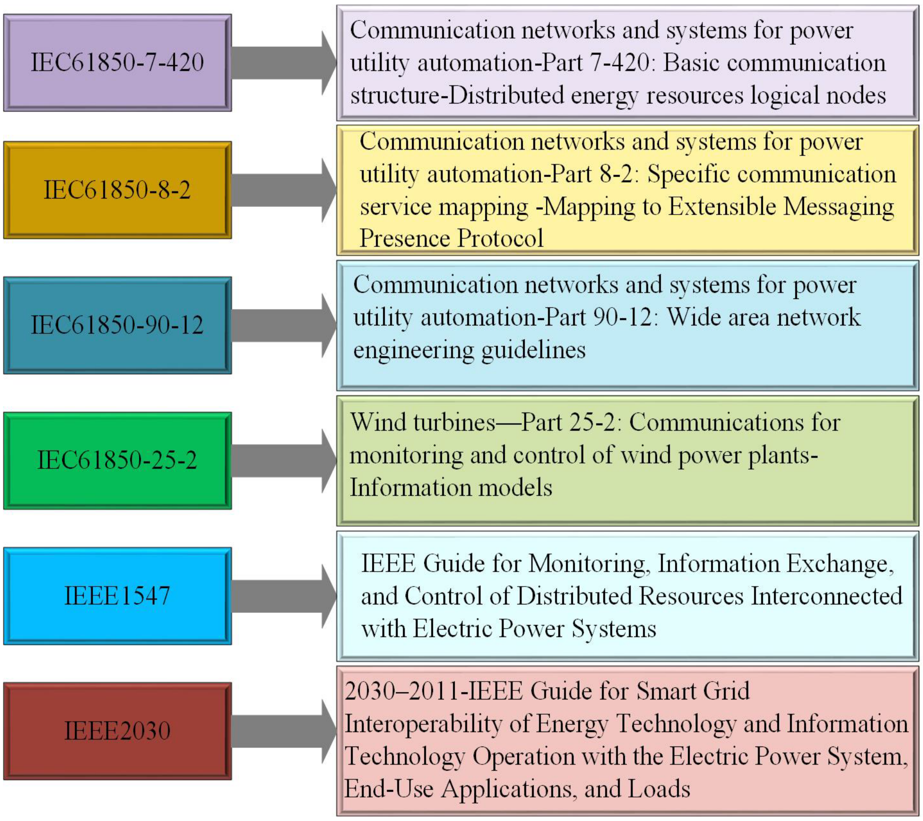

Figure 8. Some communication standards for microgrids

Table 5. Specifications of three communication systems: WAN, HAN, and FAN

Communication type	Technology type	Applications	Coverage area
HAN	-Zig-Bee -Bluetooth -Wi-Fi	-Smart microgrid -Communication between microgrid assets -In microgrids, building management system (9.6-56 kbs bandwidth with 2s-5 main latency) -In microgrids, electric vehicles charging (9.6-56 kbs bandwidth with 0.2s-2 main latency)	-Short coverage range up to hundreds of meters -Bandwidth equivalent to hundreds of kilobits
FAN	-Wi-Max -RF-mesh -PLC -Cellular	-For long distance communication -Demand response -In microgrids, distributed energy source, energy storage systems (9.6-56 kbs bandwidth with 20ms-15s latency)	-Coverage range up to kilometer -Bandwidth equivalent to tens Mbps
WAN	-Passive optic network - Cellular - Synchronous Digital Hierarchy	-Adaptive islanding -Power transmission &generation scale	-Has a wide range of coverage

4. Microgrid Energy Management System

A microgrid Energy Management System is an intelligent and automated system designed to manage microgrid systems [65]. These systems control the production, storage, distribution, and consumption of energy in microgrids. Microgrid Energy Management System controls power, ensures safety, and maintains power quality. Figure 9, shows a basic microgrid model with wind and solar sources, household, industrial, commercial, and sensitive loads, and energy management systems. In general, in forecasting production and demand from machine learning and artificial intelligence techniques are used [66]. In economic dispatch, the goal is to focus on strategies to improve the use of renewable energy sources to increase environmental benefits. Also, the unit commitment aims to coordinate the electricity generators to meet the demand. Finally, the goal of demand management is the optimal use of the load and the timing of the usage patterns to increase the financial profit. In addition, the study of various optimization techniques in the field of energy management of microgrids has become a hot research field; some of the most basic optimization techniques are shown in Figure10 [67].

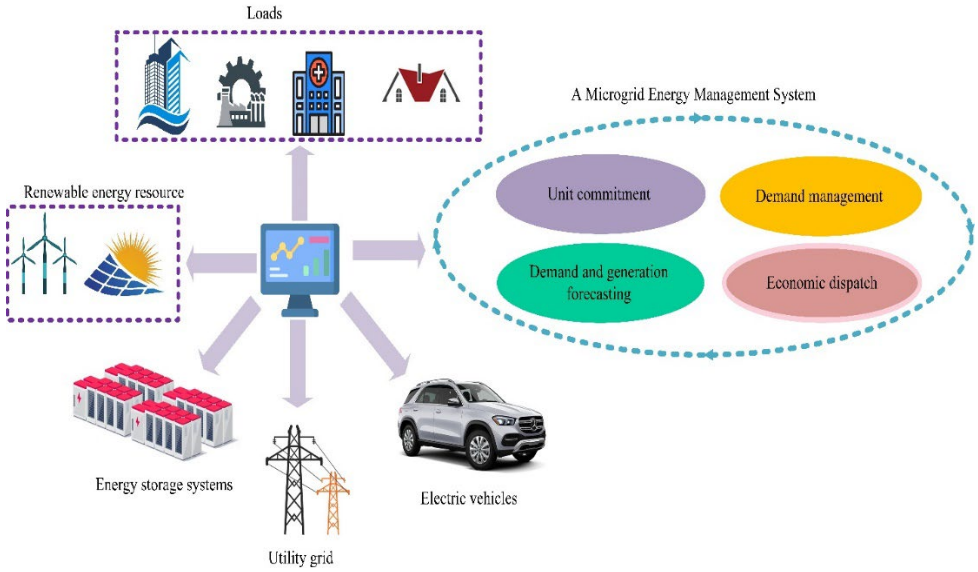

Figure 9. Basic microgrid model with wind and solar sources, household, industrial, commercial, and sensitive loads, and energy management systems

Figure 10. Various optimization techniques in the field of energy management of microgrids

5. Review the top 10 microgrid trends in 2023

Recently, electric power systems have faced significant challenges, including erosion of old infrastructure, cyber-attacks, natural events such as earthquakes, and load management problems. In addition, the advancement of technologies, the smartening of power grids, the possibility of cyber-attacks, and the increase in the lack of security lead to more concerns. This section introduces the top 10 microgrid trends to increase energy security and flexibility of energy infrastructures. Figure 11, shows the share of each of these 10 trends. Below is a review of these top 10 trends [68]:

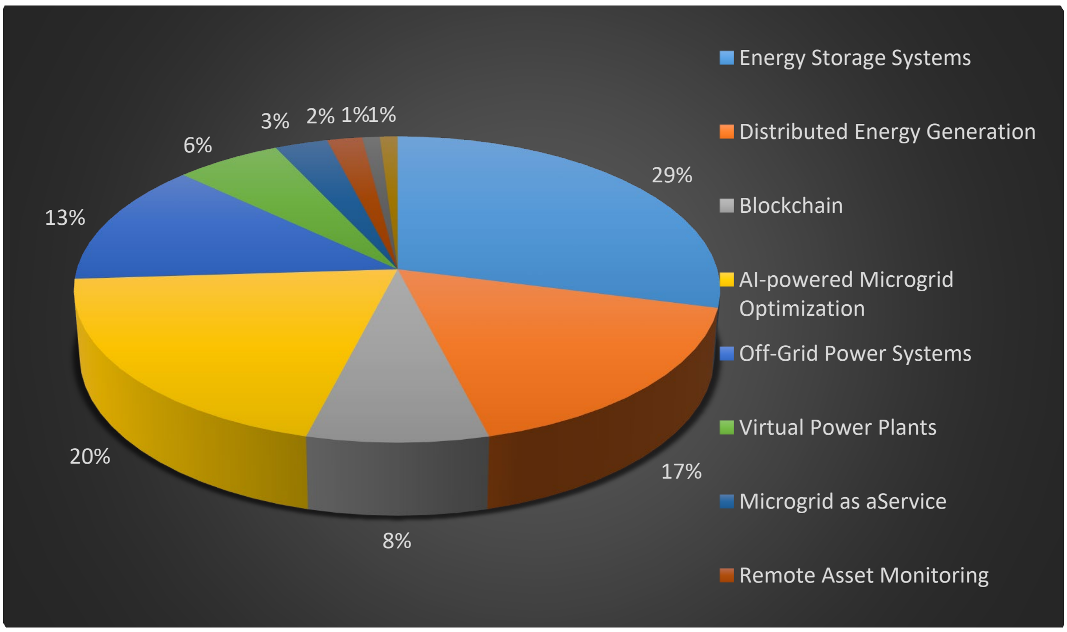

Figure 11. Statistical chart of each of the 10 trends

5.1. Energy storage system

Due to uncertainties in renewable energy sources, microgrids will be affected and disrupted. Therefore, to deal with these disturbances, startups are developing suitable technologies for energy storage, which increase microgrids' flexibility against disorders and their reliability and efficiency.

5.2. Artifice intelligence

Startups use artificial intelligence techniques as a fundamental solution to improve controllability, balance energy supply, and demand, and increase the reliability of microgrids in smart grids [66]. These techniques ensure the supply of the demand required by consumers, make microgrids use more renewable energy sources and reduce carbon emissions by reducing dependence on the main electricity grid.

5.3. Distributed energy resource

A distributed energy source uses renewable sources such as solar cells and wind turbines to generate electricity [69]. Therefore, the distributed energy source is used locally in areas far from power grids to meet energy needs. Distributed energy sources will reduce casualties. In general, distributed energy production makes renewable energy sources in microgrids more reliable and creates a sustainable and environmentally friendly energy system.

5.4. Blockchains

To manage energy transactions in microgrids, a secure and efficient system with accessibility for all grid operators should be designed. For example, this system could include a platform that makes the necessary permits for energy transactions available between energy producers. Similarly, the system can pull together information on energy consumption, prices, rates of change, and other factors that can aid in business decisions [60]. Therefore, blockchains can be a decentralized way to manage transactions. In general, blockchains protect against unauthorized access to data and guarantee the integrity of transactions.

5.5. Virtual power plant

Managing microgrids can be difficult due to some of the challenges that come with it. But the need to address these challenges is essential because microgrids are known as the best way to optimally use renewable resources in the urban energy network. Using virtual power plants for microgrids is an efficient solution for managing production and energy consumption and dealing with these challenges due to high reliability, improving efficiency, and reducing production costs[65].

5.6. Microgrid smart controller

Smart microgrid controllers are among the solutions that can be used to manage microgrid affairs best. These controllers use artificial algorithms to help control and manage different types of microgrid energy. In addition, smart controllers may increase the flexibility of microgrids by integrating energy storage and renewable energy sources.

5.7. Advanced materials

Energy production and storage capacities are the main limiting factors for microgrids, which affect the power supply of users. Therefore, startups develop energy storage systems that lead to increasing the efficiency of microgrids.

5.8. Microgrid as a service

The initial costs of installing and maintaining microgrids are one of the main challenges that have slowed their development. But microgrids can be available for small and large industries and other service organizations under the title of service. This service allows users to manage their energy needs with sustainable and more uncomplicated plans. Also, microgrids use the Internet of Things sensors and real-time analytics to achieve stable energy networks.

5.9. Off-grid power system

Off-grid power systems are intended to provide electricity independently of fossil fuel energy networks. These systems are connected to renewable energy sources such as solar cells and wind turbines [70] .In addition, the existence of energy storage systems is one of the requirements due to the presence of uncertainties, which guarantees the power supply to consumers. Also, progress in microgrid controller systems will lead to worry-free integration of off-grid power systems in microgrids, which has advantages such as supplying power to consumers in remote areas.

5.10. Remote asset monitoring

Start-ups have become fundamental and innovative in microgrids by providing innovative solutions for remote asset monitoring. Technologies like the Internet of Things, artificial intelligence, data analytics, and imaging cameras allow companies to monitor microgrid assets proactively and quickly address issues. Therefore, operators can perform optimal maintenance to increase network performance. They also inspect microgrid assets in remote areas via drones.

6. Conclusion

In general, microgrids, as part of smart grids, play a very important role in developing and improving the quality of smart grids. In the smart grid, data and information obtained from microgrids are used to improve energy management and grid efficiency. This research is designed to investigate some of the microgrids' technology and key concepts. Therefore, this review classifies microgrids into four categories: size, control strategies, and energy source type. Also, in this paper, the standards and communication systems of microgrids have been examined because the communication systems of microgrids are one of the essential components of energy management systems of microgrids. In addition, microgrid energy management systems are also essential due to the extensive use of renewable energy sources such as solar cells and wind turbines, monitoring equipment, improving grid performance, and reducing energy costs. Therefore, in this article, unit commitment, demand management, demand and generation forecasting, and economic dispatch in the form of network energy management systems have been investigated. Finally, the authors examined 10 effective micro-grid technologies to improve network performance, increase productivity, protect data, ensure energy security, etc.

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