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Control techniques for microgrids networks with energy storage systems: An overview

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Abstract Microgrids (MG) are localized, self-sufficient energy networks which utilize distributed energy sources to improve dependability, resiliency and long-term viability in decentralized energy production. Network Energy Storage Systems (ESS) have been recognized as critical facilitators within the transitioning from the conventional centralized power system into a sophisticated, self-sustaining, as well as decentralized systems based on renewable energies. Controlling distributed energy storage entails coordinating the administration of several lesser energy storages, which are generally integrated in MGAs consequence, there have been an increase in fascination with regulating elements of sharing power balance and sustainable development, boosting the system's resilience including dependability, along with maintaining a distribution State of charge (SoC). The present research provides a detailed overview of decentralized, centralized, multiagent, and intelligent controlling techniques for managing and regulating distributed energy storages. It also illustrates a possible range of functions which the storages might supply, as well as the controlling challenges and recommended solutions. This research major purpose is to represent current breakthroughs in digitalization by focusing on controlling techniques that depend on multiagent communications.

Keywords: Microgrid (MG), Energy Storage Systems (ESS), Multi-Agent, energy storage, centralization, decentralization

1. Introduction

A microgrid (MG) is a localized energy infrastructure that is developed to generate, distribute, and manage power within a certain geographical region or community (Twaisan and Barışçı2022). In contrast to conventional centralized electrical grids, MGs are operated by combining distributed energy resources (DERs), including wind turbines, solar panels, and generators, for smaller-scale applications (Subramaniam et al 2019). This self-sufficient energy ecosystem enables more effective and resilient management of energy at the local level, improving resilience and dependability (Acevedo-Rueda et al 2019). As an essential component of contemporary energy solutions, MGs provide a creative platform for incorporating energy from renewable sources and are critical for addressing the issues of varying energy requirements, a demand for cleanliness, and decentralized energy production (Chandraratne et al 2020). Efficient control strategies are critical for improving MG operations, ensuring stabilization, and utilizing the entire potential for DERs (Adewole et al. 2022). This review examines the fundamental control approaches utilized in MGs, with a particular emphasis on their incorporation through energy storage systems (ESSs).

1.1. Fundamentals of ESS in MGs

ESS plays a crucial role in MG architecture, providing dynamic solutions to the issues of periodic energy sources and demand fluctuations. ESS includes several kinds of technologies, such as pumped hydrostorage and batteries, along with flywheels, which are meant to absorb excess energy during periods of abundance and then release whenever demand increases (Chaudhary et al 2021; Georgious et al 2021). In MGs, where decentralized renewable energy sources are utilized, ESSs play an important role in ensuring grid stability, dependability, and adaptability. As a buffer that could store extra energy produced during periods of lower demand or higher renewable energy manufacturing, ESSs assist in optimizing energy distributions inside MGs (Choudhury 2022; Hajiaghasi et al 2019). This approach improves the incorporation of renewable sources and offers a dependable supply of energy during periods of shortage or when renewable production is inadequate. The symbiotic connection between MGs and ESSs demonstrates their collective possibilities for developing robust and sustainable energy ecosystems (Arani et al 2019; Sepasi et al 2023).

1.2. Controlling Techniques for Importance in MG Efficiency

The optimal functioning of MG network efficiency is dependent on the proper deployment of controlling techniques that are essential for maintaining the complex interaction of various energy sources along with loads (Roslan et al 2019). Controlling techniques serve as orchestrations and ensure that the energy streams are balanced while the entire system operates at maximum performance (Salehi et al. 2022). These strategies are critical for sustaining grid stability by proactively monitoring and modifying variables in real time, minimizing the effect of variations in renewable energy generation or rapid changes in demand (Ishaq et al. 2022). Furthermore, it allows for the seamless combination of dispersed energy resources such as solar panels and wind turbines through the coordination of their contributions while ensuring optimum application (Azeem et al 2021; Mohammed et al 2019). In simple terms, controlling techniques serve as the basis behind MG operations, allowing the network to respond adaptively to change circumstances and maximize the possibility of renewable energy resources (Al-Saadi et al 2021). While MGs have become integrated into contemporary energy landscapes, the importance of control strategies is becoming more crucial for ensuring the sustainability, dependability, and robustness of isolated energy systems. Control techniques for MGs with an ESS network are classified into three distinct categories, depending on the structure: decentralized, centralized, and distributed multiagent (Shahgholian 2021; Mohammadi et al 2021; Espina et al 2020). The conventional standard hierarchy control structure of MG modeling networks is divided into 3 stages, as shown in Figure 1, which correspond to their hierarchy structure for controlling stages as well as their specialized functions in an AC-connected MG. The stages are described in the following manner:

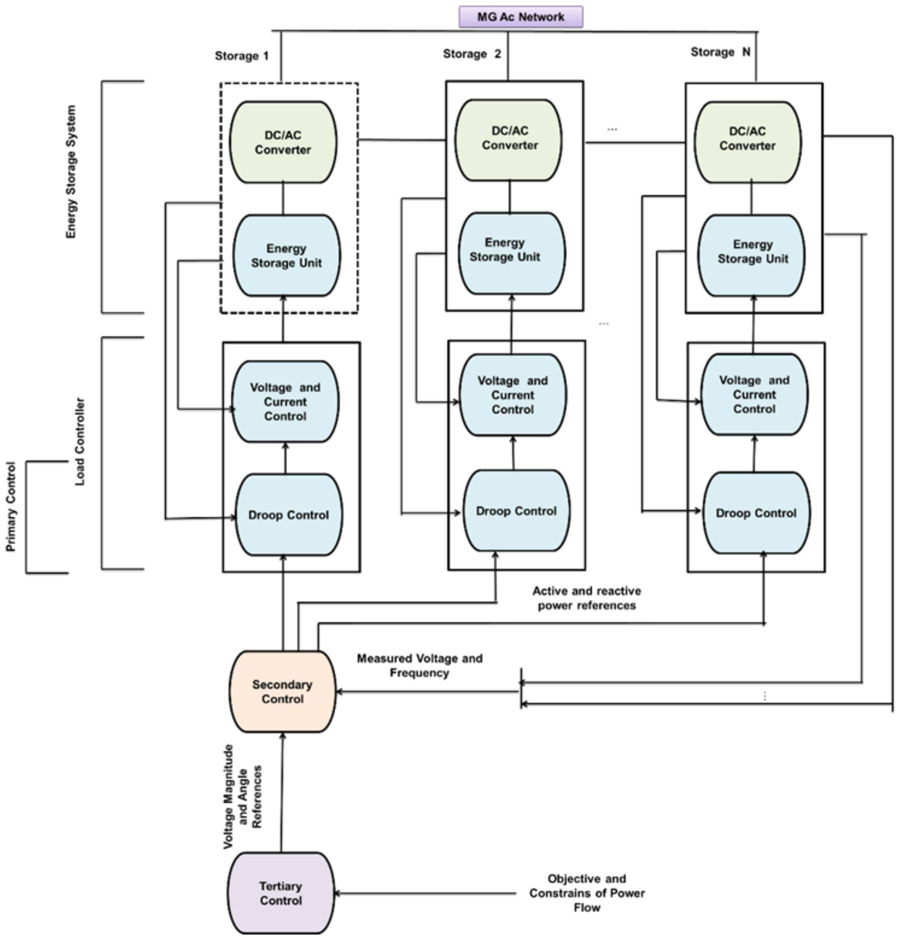

Figure 1 Hierarchy controlling structure for AC-MG.
Source: http://dx.doi.org/10.1109/TII.2018.2881540

1.2.1. Primary decentralized control

This stage regulates load sharing for DERs and storage through converter output voltage along with frequency to provide balanced and autonomous operations. Mostly, droop control balances load sharing across remote resources and storage without time-critical communication links. Figure 1 shows the AC MG main droop control at every distributed ESS. Employing measurable proactive and reactive energy offsets the frequency and voltage for a localized controller. Load participation balances MG load sharing (Muhtadi et al 2021; Legry et al 2020).

1.2.2. Secondary centralized control

The centralized secondary controller corrects the frequency and voltage offsets caused by the primary control, functioning as an observer while also providing additional functions such as reactivity in sharing power, accurate frequency regulation, and PQ compensation. Figure 1 depicts a secondary control that corrects the droop control offset to nominal terms in MG standards employing an AC MG application, depending on the observed frequency and output voltage from every ESS (Liu et al 2020).

1.2.3. Centralized tertiary control

The highest controlling stage of the hierarchy is primarily concerned with modifying the voltage setting points as well as offering optimum voltage standards. An MG maintains the flow of power, solves optimal power flow (OPF) difficulties, and cooperates with various entities to achieve balance along with sustained load sharing. Figure 1 depicts how tertiary control in AC MG regulates power flows by enforcing restrictions and standards as well as generating magnitudes of voltage and angle standards for optimum controls.

2. Decentralized controlling techniques

In an MG, the control of distributed energy storage systems (ESSs) typically follows decentralized approaches, allowing for sustainable and equitable power distribution without the need for constant supervisory controls. This system relies on localized information to reframe the energy distribution process (Alhasnawi et al 2021). Figure 2 demonstrates the conventional decentralized control of an AC MG with five distributed ESSs. In this circumstance, any one of the ESSs is managed in a localized manner, without a central or supervising controller. Decentralized droop management is a normal, conventional standardized technique for this purpose that operates in cooperation by using localized controllers to adjust the output voltages and load-sharing power of the ESS (Mehta and Basak 2021). Standard energy electronics conversion provides an interface for the MG network. The main beneficial aspect of droop management is decentralization, which eliminates the need for communication connections between distributed ESSs.

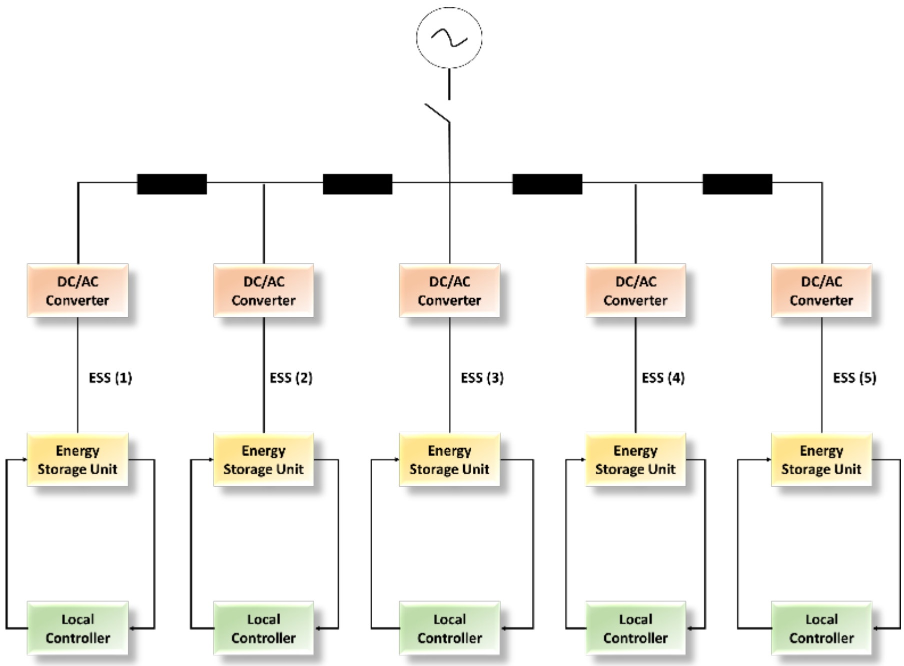

Figure 2 Decentralized control of an AC MG.
Source: http://dx.doi.org/10.3390/en14030581

2.1. Conventional droop control

Droop control is the traditional decentralized approach for controlling a distributed ESS while connecting an MG to a network via traditional energy electronics conversion. It simulates the regulator and extractor operations for synchronized generators that modify the frequencies by managing the speed along with the fuel. This demonstrates the purpose of balancing output voltages with frequency by regulating both reactive and active energy. The purpose is to create virtual resistance that varies from true resistance so that it is not impacted by operating circumstances. During a low-voltage AC MG, the output frequencies are balanced based on the proactive power (f-P), while the magnitude of the output voltages is determined by the reactive power (V-q). Figure 3 shows the conventional attributes of voltage and frequency droop characteristics.

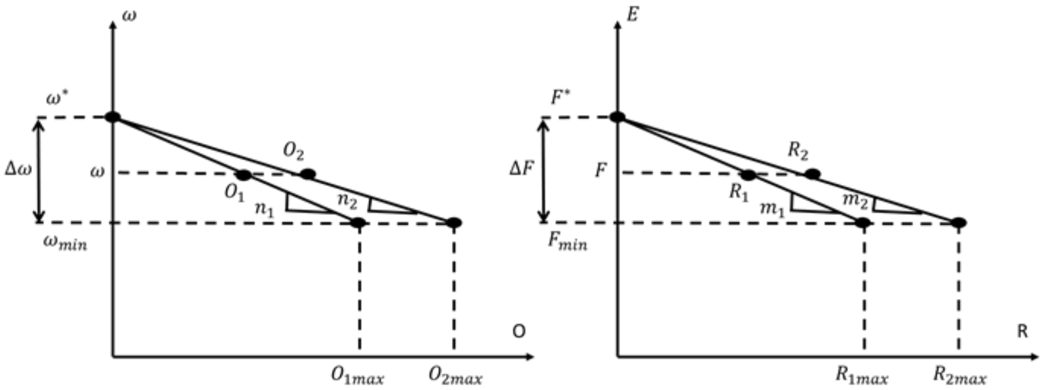

Figure 3 Conventional droop control characteristics.
Source: https://link.springer.com/chapter/10.1007/978-3-030-23723-3_22

The design for conventional droop control can be formulated by equations (1) and (2). The active energy droop coefficients (O_2) are calculated by multiplying the observed active energy (O) by the standard velocities (ω^*) to attain the required velocities(ω). However, the reactive energy droop coefficients are multiplied using the observed reactive energy (R) and subtracted from the output voltage standard (F^*) to obtain (F). n and m represents the voltage and frequency droop coefficients (Gao et al 2019).

$$\omega = \omega^* - nO \qquad (1)$$
$$F = F^* - nR \qquad (2)$$

3. Centralized controlling techniques

Centralized controlling techniques provide direct controls and individual surveillance for distributed ESS in an MG. The schematic arrangement in Figure 4 depicts the general central control of a dispersed ESS in an AC and MG with five distributed ESSs. There is direct control among the centralized controllers with any one of the ESSs in this instance. Centralized control techniques are classified into two types: secondary and tertiary control strategies. The secondary approach seeks to regulate the power qualities by adjusting the voltage or frequency, and the tertiary approach dynamically enhances the energy flow.

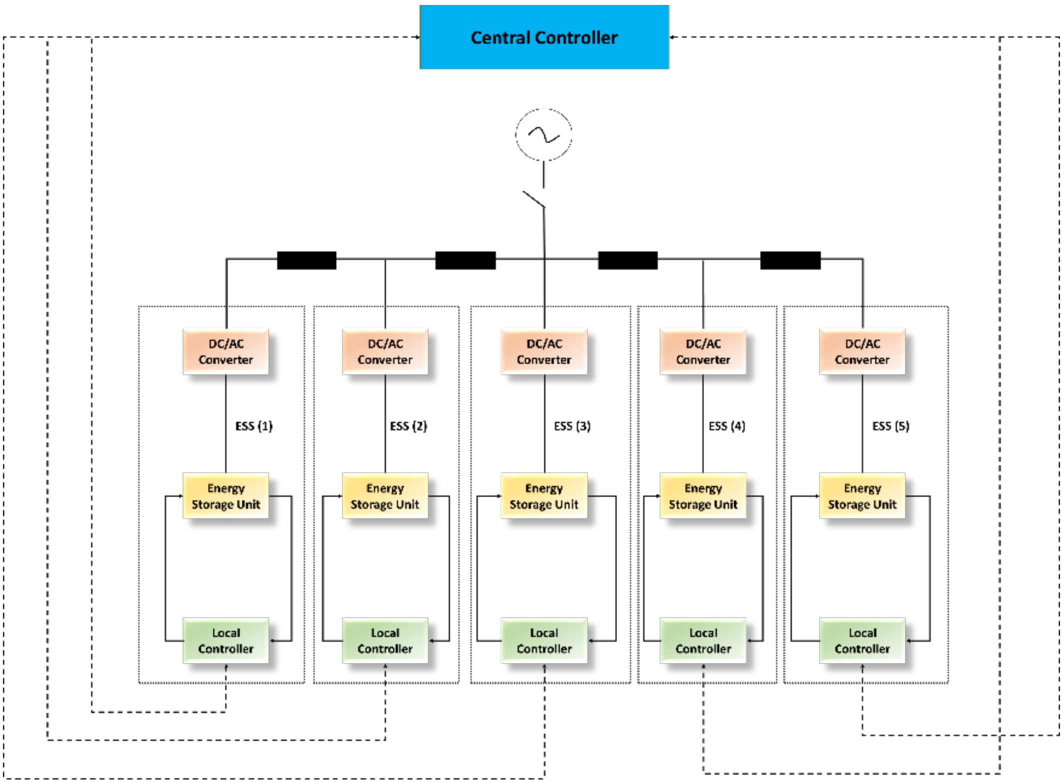

Figure 4 Centralized control of an AC MG.
Source: http://dx.doi.org/10.3390/en14030581

3.1. Centralized secondary control

The conventional MG control system improves the power quality through centralized secondary controls. Voltage or frequency restoration, discharge rate balance, loading allocation optimization, and state of charge (SoC) balancing were approaches for integrating MGs and ESSs to increase battery durability. To coordinate the ESS modes within a PV production plant, which comprises vanadium redox-flowing batteries and ultracapacitors, rule-based control techniques have been developed (Golsorkhi et al 2021; Andishgar et al 2019; Meng et al 2021).

3.2. Centralized tertiary control

Model predictive control (MPC)-based power flow management systems, two-phase development techniques, and centralized tertiary control over distribution Battery Energy Storage Systems (BESSs) in a hierarchy-based framework are successful DC-Dynamic Optimal Power Flow (DOPF) approaches in MGs. The technique improves battery discharge management by utilizing SOC-dependent power shared weights along with units controlling faults, and simulations are used to demonstrate its reliability and efficacy. Depending on the approximations employed for simplifying the issue, MG DOPF techniques can be essentially classified into four classifications. These methods include ideal real energy transfers, single/aggregated ESSs, nonconvex approximations, and convex approximations (Zhang et al 2021). Figure 5 illustrates the power networks with structures that fit such classifications.

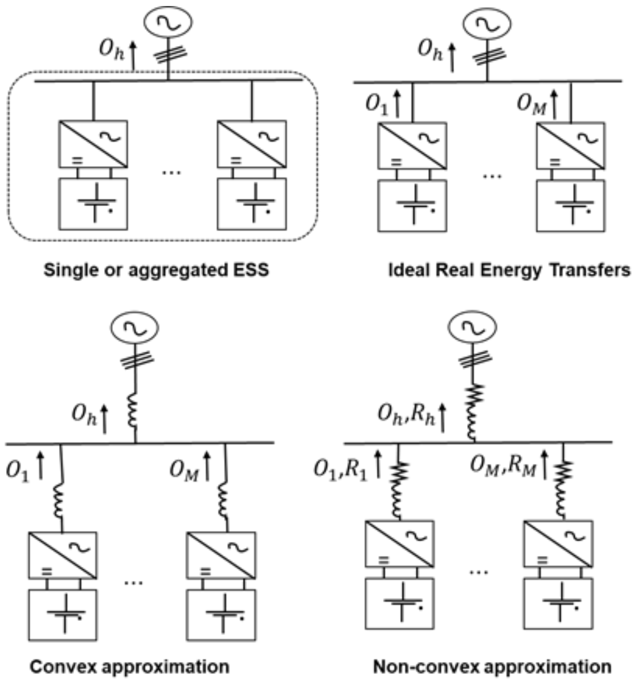

Figure 5 Power networking models for dynamically optimum power flows.
Source: https://ieeexplore.ieee.org/abstract/document/7779156

3.2.1. Single or aggregated ESS

The initial set of DOPF techniques was developed for MGs that have an individual ESS or an aggregation of energy storage capacities. Energy flows between the MG and the standard grid could be optimized, but energy flows in the ESS have not been examined. Using weighted throughput models, the DOPF technique, which incorporates the expense of battery depreciation, is recommended for the lifespan deterioration of lead-acid batteries.

3.2.2. Ideal Real Energy Transfers

The second set DOPF techniques depends on real power transfer models among distributed ESSs and assumes that every system is linked to a common network. Such approaches reduce the MG energy balancing demand to a convex optimizing problem, considering the relative SoC excluding the networking topological structure. Particle swarm optimization (PSO) addresses the DOPF issue in integrated cooling, energy units, and heating.

3.2.3. Convex approximation

The third class of DOPF techniques uses convex representations for the DOPF issue, as well as a quick and resilient solver. For networks with large X/R ratios, DC energy flow approximations are utilized, considering the reactive line impedance along with smaller terminal voltage angle variations (Garifi et al 2020). The DOPF technique employs convex OPF issue relaxation, which is accurate under specific circumstances but might be solved by semidefinite computations. A branching flow approach for convex relaxation in the OPF problem is proposed.

3.2.4. Nonconvex approximation:

The fourth technique employs a power networking framework based on nonconvex optimization, integrating mixed-integer linear optimization and nonlinear optimization, for solving DOPF problems in MGs via distributed ESS. It takes into consideration, off or on choices, and uneven phases (Shuai et al 2019) and incorporates stochastic optimization. An alternate solution uses recursion in development; however, scalability is constrained as the issue of dimensionality expands with every subsequent ESS.

4. Distributing multiagent control techniques

Decentralized controlling techniques are not capable of utilizing the overall effectiveness of distributed ESS and depend on localized information (Ali and Choi 2020). Centralized controlling techniques require sufficient architecture for sustaining communications across distributed ESSs. Both of these factors limit the maximization of integrated power and energy for storage systems (Zhou et al 2021). As a result, there is an essential requirement for approaches that integrate decentralization into communications with various units. Distributed multiagent structures were generated for this purpose, as demonstrated in Figure 6, which represents the utilization of multiagent neighbor-to-neighbor interaction networks over an AC MG composed of 5 distributed ESSs, all of which constitute autonomous agents. This process can be classified into two types: secondary and tertiary (Wang et al 2020).

4.1. Distributing multiagent secondary control

Distributed multiagent secondary control in an MG entails decentralized coordination between numerous agents that regulate energy distributions and maintain the stability of the grid. Agents work together to enhance system performance by adjusting variables such as frequency and voltage. This approach improves the MG's overall dependability and effectiveness.

4.2. Distributing multiagent tertiary control

It incorporates the dispersed controlling agent coordinates to maximize grid operations. It provides effective energy management, balance of loads, and fault resiliency, improving the entire system's dependability and sustainability in a distributed energy network, as shown in Table 1.

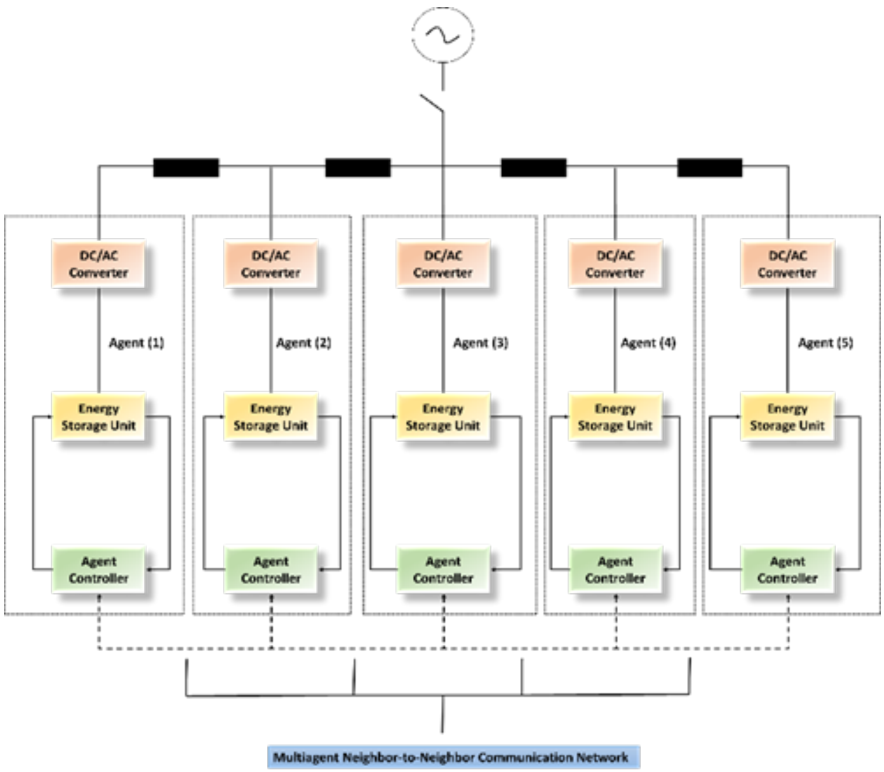

Figure 6 Control of AC MG using distributed multiagents.
Source: https://doi.org/10.3390/electronics12030565

Table 1 Summary of decentralized, centralized, and distributing multiagent control techniques.

References	Advantages	Disadvantages
Gao et al (2019)	Decentralized systems. A persistent imbalance in lines impedance.	There is no regard for SOC balancing. Due to unavoidably early current increases, a rapid procedure is not achievable.
Golsorkhi et al (2021)	An unequal load should be distributed accurately.The output voltages are properly balanced. The flow of power is an active state.	Voltage fluctuations occurs when there's an imbalance among the existing voltages, especially when the load varies.
Andishgar et al (2019)	There is no extra equipment installed. Controlling architecture with less complexities. Quick tuning.	There is no progress in terms of outcomes over earlier techniques. The identical objectives were achieved, however the controlling structure is simpler.
Zhang et al (2021)	SOC is balanced. DC voltages have been successfully restored. The system's efficacy have been achieved. Accurate battery current sharing.	Only two batteries were tested.
Garifi et al (2020)	Reduced computing time. Penalty time having little impact.	During an instance of nonsimultaneous ESS, discharges. There is no involvement of load demands responsiveness.
Shuai et al (2019)	Performance enhancement. Reduced computing time. Active in the implementation of large-scale system technologies.	After 1000 repetitions, convergence occurred. In contrast, there is a stability values that promotes the activity of massive systems approaches.

5. Reinforcement Learning with an Intelligent Controller

The integration of renewable energies with ESSs constitutes one of the contributing variables that improves system dependability by allowing extra renewable energy source production to be stored (Mahmoud et al 2021). As a consequence, multiagent communications provide the gateway to decentralization while achieving that integration. The primary objective of decentralization is the transition to intelligent, decentralized MG infrastructures. Reinforcement learning remains among the highest standards for clever intelligent energy distribution management, particularly considering the transition toward an environmentally friendly and cost-effective environment, as well as the rise of electric vehicles (Barbalho et al. 2022; Levent et al. 2019). The goal of RL agents is to improve the overall benefit through a sequence of interactions among environmental conditions, which includes energy distribution management. The ideal actions for each condition are demonstrated through the construction of qualifying benefits (Arwa and Folly 2020; Erick and Folly 2020).

6. Final considerations

MG is a transformational strategy for energy management, providing localized and self-sufficient solutions that improve resiliency, effectiveness, and long-term sustainability. ESS has been an essential part of solving the issues caused by intermittent energy sources and fluctuating demands throughout MGs. This review emphasizes the importance of effective control systems, which are classified as decentralized or centralized, along with distributed multiagent technologies and intelligent controller techniques for optimizing MG activities. Decentralized droop controls represent a conventional but efficient approach, whereas centralized secondary and tertiary controllers improve the power quality and enable dynamic energy flow management. The incorporation of distributed multiagent architectures appears to be a promising option for optimizing the potential of MG to ensure its reliability and sustainability in energy environments.

Ethical Considerations

Not Applicable.

Conflict of Interest

The authors declare no conflict of interest.

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