Review Article

Feasibility and Management of Residential Direct Current Microgrids

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ABSTRACT

Renewable energy sources, such as rooftop solar panels, are becoming increasingly widespread as the world transitions toward a more sustainable future. While traditional alternating current (AC) grids are well-established, the prospect of direct current (DC) microgrids, which can accommodate advanced battery storage systems and widespread DC loads, becomes more favorable in the context of growing global energy demand. Offering potential efficiency gains from reducing conversion losses, DC microgrids are a promising alternative for residential power delivery. This paper aims to contribute to the understanding of how residential DC microgrids can aid the global shift toward renewable energy by exploring practical considerations, advantages, and areas for further development.

Keywords: DC microgrid; renewable energy; power; AC grid; hybrid microgrid; solar panels; DC motor

INTRODUCTION

Alternating current (AC) has been the standard for electricity distribution systems since the late 19th century due to its efficiency in transmitting power over long distances and its ease of distribution. The ability to easily transform voltages has resulted in its widespread use and has made centralized generation practical. These advantages have enabled the AC architecture to be standardized across residential, commercial, and industrial sectors, and it remains the backbone of power delivery today.

However, because most contemporary domestic loads are inherently DC, the use of AC infrastructure for residential power delivery is reconsidered. Common electronics, such as televisions, LED lighting, and phone and laptop chargers, all require DC, as do widely adopted technologies like electric vehicles and solar photovoltaic (PV) systems. The increasing integration of rooftop solar PV systems in AC grid-connected homes has renewed interest in the efficiency of AC circuits.

This paper explores the implementation of DC microgrids as an alternative to AC grids for supplying power to residential buildings. Using a DC microgrid connected to a domestic DC circuit can eliminate the various AC-DC and DC-AC conversion losses associated with AC grids by keeping all sources and loads in DC, providing potentially more efficient systems of power delivery. However, a large-scale residential DC microgrid presents significant challenges. The problems addressed in this paper include complex fault protection

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schemes arising from the lack of a natural zero-crossing of current, low grid inertia, and the need to replace AC motors with DC motors in appliances–such as washing and drying machines, refrigerators, and air conditioners–which present design and cost issues. The purpose of this paper is to provide a technical review of the challenges, benefits, and future research aspects of residential DC microgrids with an emphasis on evaluating hybrid architecture and emergency management system (EMS) strategies using past experimental results and data.

TECHNICAL CHALLENGES AND PROTECTION IN DC MICROGRIDS

In typical AC residential settings, solar photovoltaic (PV) panels generate electricity in DC, which is then inverted to AC for connecting to the grid. This AC power is converted back into DC for battery storage, only to be inverted again into AC to supply household wiring. Additionally, when charging electric vehicles (EVs), the AC voltage undergoes another conversion to DC for the EV's internal DC load. The series of multiple conversion stages results in cumulative energy losses and lower overall efficiency.

Although offering a favorable alternative to reduce these conversion losses, DC microgrids require complex fault protection schemes and solutions to overcome low grid inertia. Additionally, to implement a fully DC residential circuit, large AC loads in appliances, such as refrigerators, washing machines, and air conditioners, must be replaced with DC motors. While upfront costs for DC equipment may be relatively high, the potential long-term savings from improved energy efficiency can offset these expenses.

Fault Protection

The sinusoidal nature of AC systems, which have voltage polarity and current switching many times per second, provides a natural zero-crossing for breaking high-current circuits and clearing faults. DC systems lack the natural zero-crossing, posing significant challenges to safety implementation during faults. The absence of such a zero-point in direct current during a fault, such as a short-circuit, causes self-arcing–or sparks that maintain a conductive path even when a switch opens. The presence of self-arcs during switching or fault clearing can lead to significant dangers to household safety. They can damage circuit breakers, leading to contact corrosion, and sustained overcurrent may harm converter semiconductors (1). This is an important problem in DC systems, contributing to the heightened complexity and cost of protection mechanisms compared to those of AC systems.

Traditional protection mechanisms often struggle to rapidly respond to the DC fault currents as described above. To address these limitations, solid-state circuit breakers (SS-CBs) are being explored for their "ultra-fast protective action" and arc-free intervention achieved through semiconductors as a reliable solution for a variety of fault types, including ground faults, voltage deviations, and overcurrents (2). Moreover, recent simulation results confirm the efficiency of a particular mechanical DC circuit breaker (DCCB) model in eliminating DC faults in future DC networks (3). The unidirectional nature of DC voltages and the converter-induced current limitations serve as challenges to the cost and complexity of reliable fault detection systems.

Inertia

In an AC grid, the rotational kinetic energy of spinning generators constitutes its inertia constant. The numerous generators that make up a power grid are synchronized on the same frequency and rotate in tandem to create the grid inertia (4). Inertia's most salient role in AC grids relates to the response to contingency events, which may be defined as a drop in generation. This drop creates an imbalance in supply and demand, resulting in an inertial response: remaining generators convert their rotational kinetic energy into power generation, slowing down the generators to provide time for the online generators to detect changes in frequency (4). Once these generators initiate Primary Frequency Response (PFR), the generator output increases, and the frequency stops declining, as shown in Fig. 1. Under Frequency

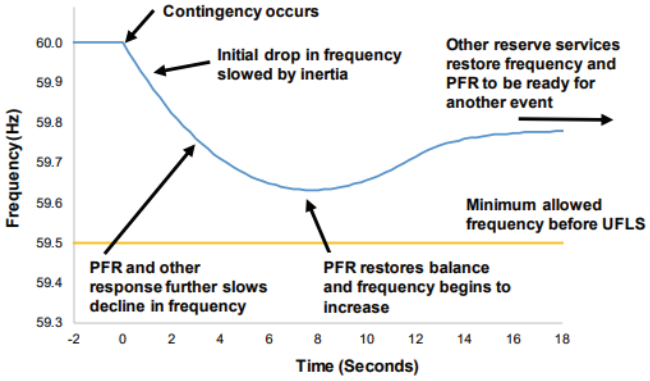

Figure 1. Generators initiate Primary Frequency Response (PFR) to prevent grid collapse after a drop in frequency caused by a contingency event (4).

Load Shedding (UFLS) is an emergency mechanism that automatically disconnects loads from the grid after multiple contingency events and/or if the grid frequency drops below a particular frequency, preventing complete system collapse.

However, unlike AC systems, DC grids lack spinning generators and rotational kinetic energy (inertia), making them more susceptible to rapid voltage deviations during contingency events. Because non-rotational power electronics contribute little to no inertia in DC grids, there is a faster Rate of Change of Frequency (RoCoF) during disturbances, which increases the risks of relay tripping and successive failures that require UFLS (5). In AC grids, synchronous generators provide damping that stabilizes the system. In contrast, DC microgrids' lack of generator inertia makes them prone to instability. However, an established solution is the use of energy storage systems (ESS), which allow energy to be stored for later use and can be used to prevent this instability. ESS in the microgrid, such as batteries and supercapacitors, store energy and provide rapid power absorption, which can help stabilize the DC grid during disturbances. Additionally, virtual synchronous generators (VSGs) and machines (VSMs) produce virtual inertia by using a control loop based on capacitors or converter-based controls (6). Additionally, the kinetic energy in the rotor of a permanent magnet synchronous generator, such as a wind turbine, the energy stored in batteries, and the energy from the grid can help enhance the inertia of a DC grid (7). However, these methods are still experimental and may not fully prevent DC voltage instability under power variation.

Furthermore, the problems associated with low grid inertia in DC systems further accumulate as the number of power electronic converters (PECs) in the system increases. This is because, as numerous renewable energy sources (RES) are annexed to the grid using PECs, the system inertia decreases due to their absence of rotational inertia (2).

DC Motors

Beyond the well-documented challenges of grid protection and stability, a less explored yet significant area is the integration of DC motors within household appliances. While AC motors are standard in home appliances, transitioning to a fully DC-powered residential building introduces several appliance-level design changes.

However, despite current architecture incompatibility and higher costs for DC-powered appliances, research has shown significant advantages of DC motors in place of AC motors, specifically in energy savings. Glasgo *et al*. analyzed 120 different AC-wired homes in Austin, Texas, using a Monte Carlo simulation to quantify cost and energy savings from switching to direct-DC circuits. They explain that while fully converting equipment to DC doubles levelized electricity costs due to high equipment prices, they found energy savings of 9-20% with solar PV integration, which increased to 14-25% with battery storage (8). Moreover, converting air conditioning units to DC notably reduced costs and generated 7-16% site energy savings (8). Still, they conclude that limited market availability for DC appliances and utility programs designed only for AC utility grids remain significant barriers. This can change with widespread adoption of DC microgrids, government incentives, and the ever-increasing cost of AC grid power.

Furthermore, Garbesi *et al*. concluded that nearly all major household appliances can be replaced with more efficient DC counterparts. While such equipment incurs a marginally higher initial cost for full residential use, it provides significant savings in the long run (9).

For AC grid-connected homes, the primary motors in home appliances consist of AC induction motors (larger loads) and universal motors (smaller loads) (10). DC motor alternatives include brushed DC, brushless DC motors (BLDC), permanent magnet DC (PMDC), and switched reluctance motors (SRM) (11). Data shows BLDC motors are much more efficient than both types of AC motors described earlier. For constant speeds, Garbesi *et al*. found that they save about 5–15% energy. In variable speed setups, they perform even better: variable speed BLDC motors in furnace fans and boiler circulation pumps resulted in predicted energy savings of 30% over AC motors (9).

Beyond the produced energy savings, DC products excel in efficiency. Findings suggest DC product efficacy of nearly 10% greater than AC counterparts in compact fluorescent lamps (CFLs), with even greater efficiency gains in light-emitting diodes (LEDs) (9). Energy Star certification is a United States EPA program that certifies a product or building meets specific energy efficiency standards. A 2014 Energy Star publication reports that BLDC motors achieve cooling efficiencies close to twice the minimum requirement for Energy Star certification when run in existing variable speed refrigerant compressors in air conditioner condensing unit applications (8). Furthermore, DC products in refrigerators and freezers used significantly less energy: on average, less than half of the energy of their AC

counterparts, as shown in Fig. 2 (9).

Another area of savings offered by DC appliances is the absence of rectification and subsequent losses, especially when households utilize both solar PV and plug-in electric vehicles (PEVs). Traditionally, when an AC grid supplies power to PEVs, which have internal DC loads, rectification from AC to DC is necessary. However, given a DC line from a microgrid, supplying PEVs would simplify to just a DC-DC converter, thereby cutting rectification losses (12). The concept of elimination of rectification losses is also applied to lighting systems and consumer electronics. Conventionally, AC voltage supplied from the grid is rectified, stepped down in a DC-DC transformation stage, and consumed by electronics' internal DC loads. Again, voltage supplied from a DC microgrid would eliminate rectification and associated losses (13).

Many studies comparing power electronic converter efficiency in AC and DC systems have found positive results associated with DC systems. Haroon *et al.* considered multiple PEC efficiencies and rooftop solar capacities. Their comparative analysis revealed DC efficiency advantages of 1.966%, 1.41%, and 1.17% as compared to AC in the scenarios considered (14). For this study, power loss in PECs and line loss were calculated for both AC and DC distribution systems over a 24-hour period. The power loss in AC was significantly greater for the corresponding time of day than that of DC, as shown in Fig. 3, where β is the loss factor, (a) is the power loss in the AC distribution system, and (b) DC distribution system.

ARCHITECTURE AND POWER FLOW

DC-coupled Systems

A DC microgrid radial configuration topology is presented with DC and AC loads, renewable energy sources (RESs), and energy storage systems (ESSs) connected by a single DC bus in Fig. 4. Power converters, DC/DC and AC/DC, are shown.

This is the standard power flow for a DC-coupled system. The structure contains various distributed energy resources (DERs) connected to a DC bus, typically with DC-DC converters. The power remains in DC form until absolutely necessary, for example, feeding into the AC grid or powering an AC motor. This system is ideal for solar PV, batteries, and DC loads, such as LEDs or EVs, and is thus more reliable than AC networks due to a reduction in conversion stages (16). However, they aren't as well-suited for AC appliances, grid, and RES integration, such as the wind turbine shown above (17). Integrating a wind turbine into a DC-coupled configuration typically necessitates a permanent magnet synchronous generator, which reintroduces power conversion stages and undermines the efficiency advantages of a fully DC architecture.

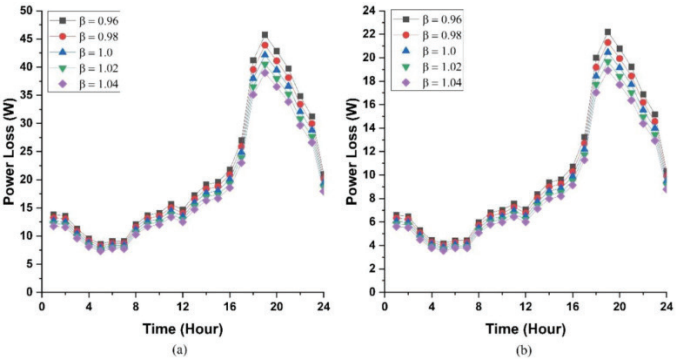

Figure 3. Power loss in power electronic converters (PECs) and lines over 24 hours in (a) an AC distribution system and (b) a DC distribution system (14).

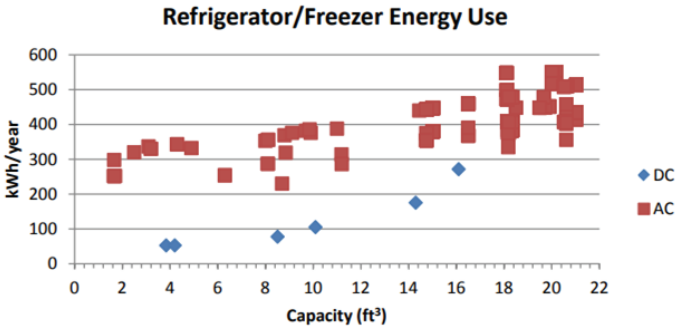

Figure 2. DC products in refrigerators and freezers, shown in blue, consume on average less than half of the energy used by their AC counterparts, shown in red [9].

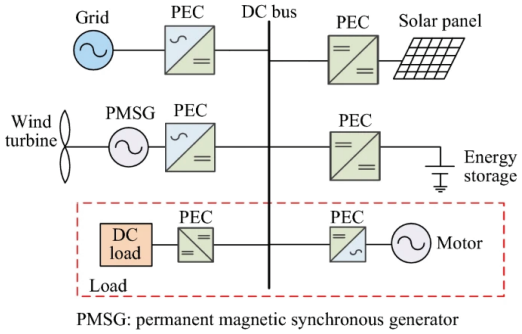

Figure 4. Radial configuration of a DC microgrid with AC and DC sources and loads connected through a single bus (15).

AC-coupled systems

In an AC-coupled system, the power flow is a common AC bus, which connects to a unidirectional PV inverter and a bidirectional battery inverter. The bidirectional electricity meter is connected from the AC bus to an optional grid switch, which connects to the grid. All DC sources and loads must be converted to AC to interact with the grid and other AC devices, such as a domestic load. A drawback of this system, noted by Yianni *et al*., is that if the battery inverter shuts down, the PV inverter will shut down automatically as well and will no longer be able to provide power. A significant implication is that if the grid shuts off or is non-operational, such as in the case of a grid outage, the PV inverter cannot provide power to charge the battery (18). The grid switch is used to isolate the grid during a grid outage to allow the PV system to provide backup power to the load. Beyond the AC-coupled and DC-coupled grids, interest has grown in hybrid AC/DC microgrids for their greater flexibility in supporting different RES types, described below.

AC-DC coupled systems

Hybrid AC/DC distribution networks (HDNs), which are grids that leverage the positive aspects of both AC and DC grids, consist of individual AC and DC networks that are interlinked by a bidirectional converter. When considering their efficiency, Zhang *et al.* found that HDNs are able to transfer 150% more power than AC distribution networks. HDNs, for example, the one in Fig. 5, have greater hosting capacity for RESs, battery storage systems, and EVs than existing AC infrastructure (20).

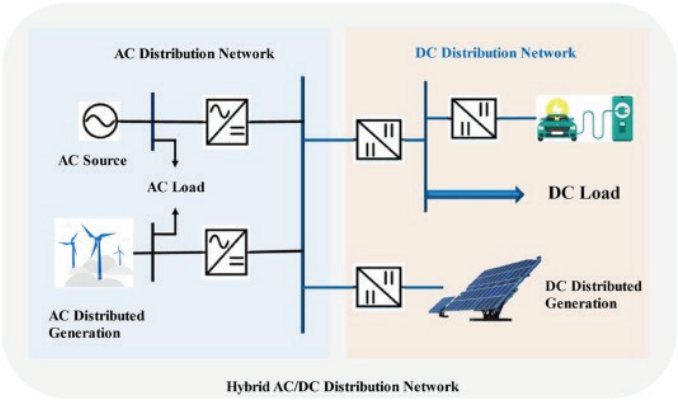

Figure 5. Hybrid AC/DC microgrid radial configuration with multiple AC and DC loads capable of more efficient power transfer than traditional AC distribution networks (21).

Fig. 5 shows an HDN where both AC and DC sides share a common bus. However, HDNs are more commonly represented by a configuration in which both the AC and DC buses are interconnected by a bidirectional converter, where loads and sources are connected to each bus depending on their type. For instance, Fig. 6 describes such a configuration.

HDNs, as shown, can reduce conversion losses for DC loads and maintain AC compatibility. As a more resilient structure, Yi *et al.* concluded that it is easier to isolate parts of the system during faults. Hybrid grids are particularly ideal for remote residential network communities that traditionally rely on localized generation, such as diesel generators, and lack durable grid connections. Oulis Rousis *et al*. developed an autonomous microgrid (Fig. 6) in a village in Kea, Greece, because no distribution network existed in the site's location, and putting a dedicated line through that site would have required significantly more capital expenditure than the construction of an autonomous microgrid. During periods of low solar PV output, such as cloudy days, the diesel generator can supply the necessary power to the DC bus, while during times of surplus solar generation, it helps maintain energy balance, therefore supporting the viability of fully remote hybrid microgrids (22).

Converters

Voltage source converters in hybrid systems offer voltage and frequency stability in distribution networks. While active power is defined as the amount of usable power in a grid that performs real work, reactive power oscillates between the load and source and doesn't do real work, but is required to maintain voltage and

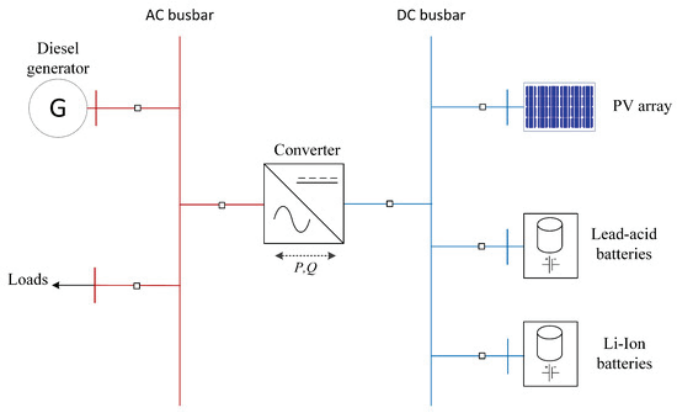

Figure 6. Hybrid microgrid with separate AC and DC busbars connected with a bidirectional converter (22).

magnetic fields in AC systems (23). DC networks don't contain reactive power; therefore, in the DC side of HDNs, voltage regulation is driven by DC active power. Because VSCs can control active and reactive power independently, the voltage control on both sides is more flexible (24). Therefore, combining existing AC infrastructure with DC networks will enhance voltage stability in the system due to flexible power flow between AC and DC (25).

The absence of reactive power in DC systems also serves as a benefit when considering power factor. In AC grids, when voltage and current sinusoidal waveforms are out of phase, the ratio of true power to apparent power, representing power factor, deviates from one. When appliances have a power factor lower than one, they draw more current than necessary to deliver the same real power, which is inefficient and increases resistive losses. While power factor correction can help, such as adding a capacitive load to a lagging inductive circuit, difficulties may arise in maintaining a high power factor across varied residential loads in AC systems. However, due to the absence of voltage oscillation in DC systems, they lack reactive power and subsequent power factor concerns. Therefore, power factor is insignificant in devices with steady power consumption, making DC systems more efficient.

Series-connected active filters help regulate reactive power in the AC side of an HDN. Active filters, connected in series with the grid through a coupling transformer, operate as a voltage regulator and mitigate voltage harmonics and flickers produced by nonlinear loads, such as induction furnaces, which have a nonlinear voltage-current characteristic that creates harmonic currents (26, 27). If a nonlinear load generates a voltage harmonic, the series active filter (Fig. 7) provides a high impedance that prevents current flow from the load to the source.

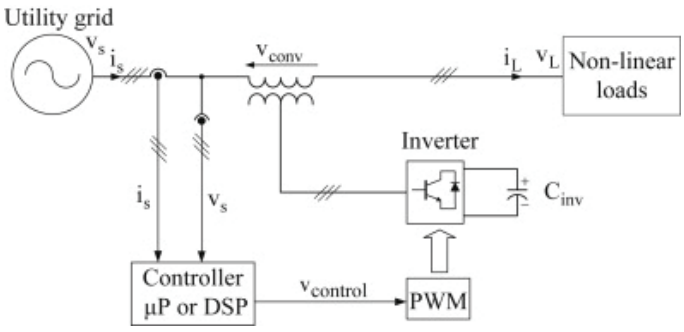

Figure 7. Series active filter inserted in series between AC source and nonlinear loads to regulate the AC power in a hybrid distribution network (26).

AC/DC Converters

The voltage source converter (VSC) replaced current source converters (CSC), which were designed after the first three-phase diode rectifier. CSCs, current dependent and unidirectional converters, were used to integrate a DC-link into existing AC distribution networks in several past studies. However, such studies did not extend to complete HDN implementation and power exchange, which require the bi-directionality and voltage-dependency of VSCs (25).

DC Microgrid Topologies

Topology selection of DC microgrids helps optimize specific renewable energy sources and is configured based on practical demands. This section describes a few of the more common topology designs.

Single-Bus

As the most straightforward structure, the single-bus topology has a simple, cost-effective design ideal for proof-of-concept, small-scale setups with limited residential scalability. The single bus allows for centralized voltage control, but is more susceptible to voltage drops or harmonics and has poor fault isolation. Additionally, due to its long feeders, the single-bus configuration faces higher resistive losses, creating greater line loss sensitivity.

Multi-Bus Topology

Multi-bus topology improves single-bus reliability by adding additional voltage levels. Because the faults in one bus segment may be isolated without disrupting the entire system, multi-bus topologies provide improved fault isolation compared to single-bus topologies (28). In a multi-bus architecture, power is transferred between buses that have similar voltage levels via static switches (29). Compared to single-bus, this type of architecture provides higher resilience to localized disturbances and can support diverse types of DERs on different voltage levels at once. Fig. 8 depicts one such structure.

Reconfigurable Topology

Flexible grid configurations accommodate several RESs and provide external grid connections for AC sides and islanded mode connections for the DC side (30). One such configuration is the Ring (or Loop) Configuration. Ring configurations allow for alternative power paths, meaning that if one segment fails, power can still flow in the opposite direction to reach all loads. Besides faster fault isolation support, ring configurations provide

bidirectional power flow, which can prove useful for distinct DERs that have variable generation, from solar arrays to wind turbines, as shown in Fig. 9.

An intelligent electronic device (IED) in the system, shown as an intelligent electronic breaker in Fig. 9, isolates that particular fault segment during failures by operating switches (32). Combined with its rapid fault response, the isolation of the DC side of this system from the AC grid during disturbances makes the ring-loop configuration reliable and ideal for industrial facilities and remote microgrids where constant uptime is critical (2).

Another important architecture is the radial configuration, where an AC system is connected to a DC system via a single/multi-bus and may be connected in series or parallel. An AC-DC converter may be connected in series with the AC and DC network, with a grid switch in between. Because only a single bus is required to manage all power flow, the radial configuration is ideal for low-voltage applications (33).

The final configuration discussed in this section is the zonal type (Fig. 10).

This structure is divided into zones that are each connected by two DC buses and are supplied with power by the AC grid. Each zone contains its power supply, consisting of AC or DC energy sources and multiple switches, providing a flexible configuration (34). New DERs can be added without overhauling the entire microgrid, therefore supporting modular expansion (35). Since power is supplied locally in each zone, transmission losses are minimized compared to a centralized supply setup.

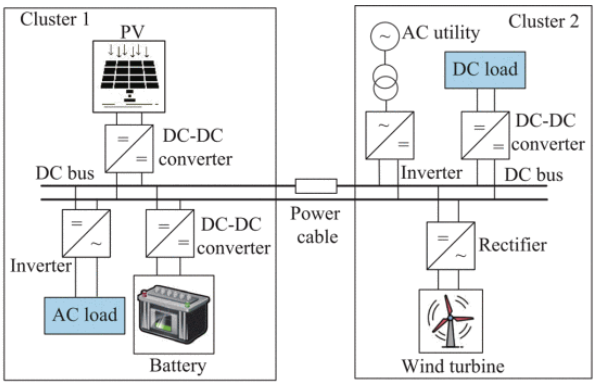

Figure 8. DC microgrid multi-bus topology with multiple voltage levels and buses to improve reliability compared to single-bus topologies (2).

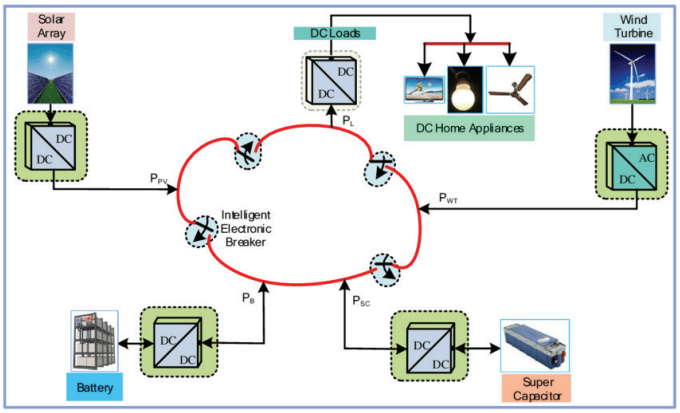

Figure 9. DC microgrid loop configuration allows for alternative power paths and bidirectional power flow, resulting in faster fault isolation (31).

ENERGY MANAGEMENT SYSTEMS AND OPTIMIZATION STRATEGIES

Energy management systems (EMS) help microgrids handle blackouts and other grid failures by managing variable energy sources and ensuring load stability. EMS decides when to charge or discharge batteries, which energy source to use, and how to balance supply and demand, and much more. This section outlines EMS operations and response strategies in microgrids.

Microgrid Context

The EMS, in the context of microgrids, acts as a central control system that manages energy generation, storage, and consumption (36). For AC systems, EMS primarily regulates frequency and reactive power, and it schedules generation units. For DC microgrids, the EMS focuses on voltage regulation and minimizing

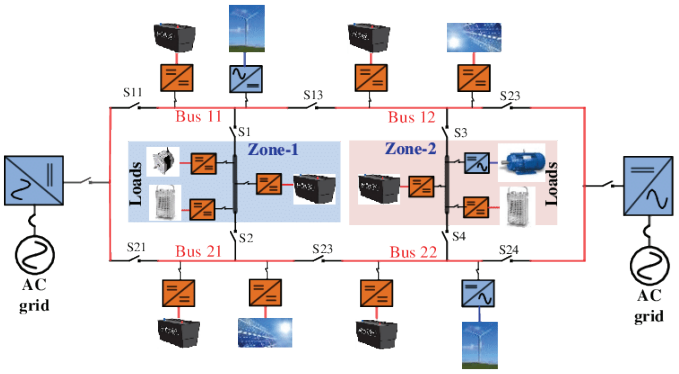

Figure 10. Zonal type microgrid topology contains divided zones with localized power supply, resulting in flexibility and lower transmission losses (34).

conversion losses. Due to some fluctuation in solar PV generation, EMS is particularly important in preventing deep charging and discharging cycles to preserve the lifespan of energy storage systems (ESS) (37, 38). In HDNs, EMS architecture is more advanced due to the increased complexity of coordination between both AC and DC networks, including mode switching between grid-connected and islanded modes. Hosseini *et al*. propose a novel EMS model designed for a hybrid system and optimized by a MATLAB algorithm to meet active and reactive power requirements associated with HDNs, as well as battery energy storage (BES) efficiency. Comparing their obtained BES efficiency to that of a conventional EMS, their MATLAB and experimental results showed "improvement in long-term BES efficiency," highlighting the "effectiveness of the suggested approach" (38).

Architecture

The typical architecture of EMS includes three layers: management, automation, and field level (39). The management level serves as a supervisory layer, where data analysis and system logic take place via human-machine interfaces. The automation tier executes control functions by communicating through protocols to local controllers in the grid. Finally, the field, or plant, level consists of the actual physical devices, including sensors, meters, and actuators (which execute control actions based on sensor-collected data) that are connected to controllers through a fieldbus for real-time control (40, 41).

Key components of the EMS comprise forecasting modules, optimization engines, a scheduling module, and human-machine interfaces (HMI) (42). Zhakiyev *et al*. proposed a forecasting model integrated into the EMS for a microgrid to serve one-day-ahead forecasts. Their EMS model, with load forecasting integrated to optimize power consumption and microgrid unit operation, was able to achieve a 17% cost reduction for the 30-day period compared to an EMS model without their load forecasting model (43).

More research interest has been demonstrated in the integration of computational intelligence for EMS, such as in Leonori *et al*.'s study (44). For instance, to improve microgrid efficiency, Aguila-Leon *et al*. proposed the use of artificial networks in EMS, and it was simulated in a MATLAB/Simulink environment using existing experimental data. Their model showed a decrease in errors by 56% to 59% for single-step and multi-step energy forecasts (45). While the proposed model demonstrated strong performance using investigational data, its applicability to broader, real-world scenarios remains uncertain and comes with limitations, especially due to RES fluctuations under meteorological conditions that impact electricity generation (46). Moreover, the model's potentially high computational demands could hinder its feasibility for rapid response to faults (47, 48).

Control Strategies

EMS systems include complex control strategies to operate. Designs in core control strategies, including centralized, decentralized, distributed, and multi-agent EMS systems, are explored to meet the specific needs of AC, DC, and hybrid microgrid architectures.

In centralized EMS systems, a single controller gathers all system data and makes operational decisions. Suitable for small-scale microgrids with limited DERs or simpler topologies, centralized EMS becomes inefficient as system complexity grows. A central management system means that if the controller fails, the entire system may be compromised. Additionally, because a single controller is responsible for managing both local and global decisions, centralized EMS systems face heavier computational loads and more communication traffic (49, 50).

On the contrary, the decentralized EMS contains local controllers and is ideal for zonal or multi-bus topologies. With local control systems in a decentralized EMS, the response speed is much higher, and data can be exchanged between different sectors, thereby maximizing efficiency received from the power system (51). Unlike the centralized EMS, local failures no longer threaten complete EMS collapse in decentralized systems, and they can easily accommodate new DERs.

As smart grids guide future research direction, a distributed EMS system, such as multi-agent systems, can use negotiation and collaboration between local agents. A multi-agent distributed (MAD) EMS is a type of decentralized EMS where multiple intelligent agents collaborate to manage power generation, storage, and consumption without relying on a central controller. Fig. 11 depicts a diagram of a MAD EMS for real-time load management.

Contrary to direct load control, used in centralized EMS, a distributed load control using a MAS is a more effective approach for improving demand response. For instance, Dai *et al*. implemented a distributed load control with a MAS for air conditioning units, which are sensitive to temperature variations, and reported a significant reduction of 2,562 kWh in electricity, which accounted for 19.7% of the electricity consumption using the conventional (direct load) control (53).

Communication Infrastructure and Cybersecurity

Energy storage systems, distributed energy sources, and smart metering architecture form the core components of the DC microgrid. When exposed to cyberattacks, these components can cause problems and possibly disrupt operations (54). The main challenge to providing defense is creating and maintaining secure communication channels between the components. Without secure communication, it is challenging to monitor the system continuously or ensure cooperation among the components mentioned above (54). It is particularly problematic when cyberattacks transcend the digital realm and extend to the physical domain. This occurs when the cyberattacks invade the system and render the machine unable to perform basic commands, allowing the breach to move from the digital to the physical environment (55). Software applications, such as Security Information and Event Management (SIEM) systems, Intrusion Detection Systems (IDS), and vulnerability scanners, monitor the system's digital environment for anomaly detection and send real-time alerts (55). These tools, when incorporated into the cybersecurity framework, allow for early threat detection and rapid response to security breaches.

Future EMS research

Future EMS research is concentrated on developing smart EMS systems, with several studies exploring the integration of artificial intelligence in EMSs. Neural networks were simulated with load predictive control to manage energy in (56). Their results showed that their proposed models demonstrated feasibility and several benefits. Aside from MAS EMS, neural networks and Fuzzy logic-based EMSs are being explored. Vivas *et al*. proposed a fuzzy logic-based EMS for a microgrid integrating both battery and hydrogen ESSs. Their findings showed that the system effectively met load demands while also satisfying technical and economic performance criteria (57).

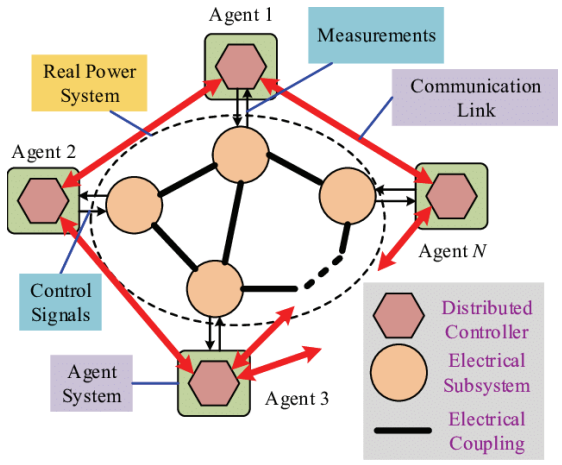

Figure 11. A multi-agent distributed emergency management system with N-agents shows decentralized intelligent agents that manage power generation, consumption, and storage in the grid (52).

MARKET, POLICY, AND ECONOMIC CONSIDERATIONS

The real-world implementation of microgrids, especially HDNs, depends on market, regulatory support, and economic incentives. Aside from engineering, HDN deployment relies on existing energy policies and consumer behavior.

Some challenges associated with deploying distribution networks include inadequate funding, power grid inflexibility, insufficient knowledge about RES integration among skilled personnel, and a lack of social acceptance and experience with regulations and planning (58, 59). Additionally, due to the high availability and low costs of RES generation units, grid connections become more common, but come with high overall project capital expenditures (60). Because it is often unclear who bears the cost for grid connections in remote, small-scale areas of developing countries, regulatory authorities must take the responsibility for the management of connection offers (61).

CONCLUSIONS

Stronger trends towards solar PV usage make hybrid AC/DC distribution networks (HDNs) a promising solution for renewable energy source (RES) integration while maintaining compatibility with existing AC infrastructure. The various topologies explored in this paper (radial, ring, zonal, etc) each have tradeoffs in fault tolerance and efficiency, and proper selection is important when deciding system-level design.

Beyond architecture selection and design, emergency management systems (EMS) are important for real-time control and optimization of loads and sources within a microgrid. The various control strategies discussed in this text each serve different levels of grid complexity; however, distributed systems are the most favored for scalability. Additionally, new areas of research encompass artificial intelligence and smart forecasting

tools for EMS systems.

Beyond the technical challenges and solutions presented, residential microgrid deployment requires significant shifts in public policy. While instruments such as smart metering incentives help initiate development, broader adoption requires stronger long-term policy backing and sufficient funding.

Microgrid feasibility relies not only on technical innovation but also on the effective interdisciplinary collaboration between economic and policy sectors to support resilient infrastructure. Microgrids, especially hybrid networks, are a crucial step in a much larger path toward a more sustainable future.

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