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Microgrid Sources and Power Electronic Interfaces: A Comprehensive Review on Source Characteristics, Converter Design, Protection, Power Quality, and Energy Storage Integration

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Abstract

Microgrids have become a prospective technology in improving energy reliability, sustainability, and resilience through a combination of a variety of distributed energy sources, sophisticated power electronic interface, and energy storage systems. In this paper, there is an in-depth discussion of the source of microgrids, its fundamental features, and how it works and the criteria that may be used in selecting the source of microgrids depending on the factors involved and how compatible the source is to the system. Special focus is given to the involvement of power electronics to interface AC and DC sources in microgrids where converters allow the exchange of power in both directions, provide voltage and frequency stability, and efficient conversion of power. The review also analyzes some critical concerns of protection and coordination, discussing the problems related to fault detection, isolation, and restoration in complicated hybrid networks. The quality of power, such as harmonics, variation in voltages, and frequency variation are examined as well as modern remedies that exist to solve power quality problems such as active filters and sophisticated control measures. Moreover, incorporation of energy storage systems (ESS) in either portable or stationary format is discussed as one of the enablers of flexibility, peak load control and penetration of renewable energy. This study provides beneficial information to the design and work of resilient, efficient, and future-oriented microgrid systems by synthesizing the advances in the sources, power electronics, protection, and storage technologies.

Keywords: Microgrid, power quality, distributed energy sources, power electronics interfaces, energy storage systems

INTRODUCTION

A microgrid must be able to supply energy to its connected loads independent of the utility, so generation sources must exist within the microgrid. These sources could range from readily controlled to intermittent, to not controllable [1–4]. This could be renewable (e.g., solar PV, wind, biomass; or less frequently used such as solar thermal, hydro, micro-hydro, tidal) or nonrenewable (e.g., diesel, NG, combustion turbines, reciprocating engines, cogeneration, CHP, turbines, microturbines). The selection of energy sources needs to be adjusted to the demands on the microgrid, such as the desired generating capacity, required firmness level, ramp rate, renewable energy targets, and availability of fuel (and fuel storage requirements). Brownfield

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microgrid setups often start with some form of existing generation already onsite, such as existing diesel generators, solar panels, or cogeneration facilities. The existing generation resources influence the additional distributed generation capacity required to be added for supporting the microgrid [5–9]. Recent decreases in the price solar PV modules and other forms of renewable energy such as wind and biomass, along with energy storage, have enhanced the economic feasibility and attractiveness of renewable energy-based microgrids. Economies of scale apply across almost all the generating technologies, implying that smaller generators have a higher unit cost of installation cost compared to larger ones, and consequently a higher repetition of cost of energy for generation [10–14]. For example, a 5-kW residential rooftop solar PV system might cost about $4 per watt to install, whereas a 50 MW utility scale solar PV farm could cost $2 per watt installed. Additionally, costs decline with increase in technology maturity. For example, solar PV panel costs are steadily declining. Furthermore, there are technology-specific considerations. Solar-powered remote microgrids face several inherent challenges. One key issue is the maintenance of solar modules, as their efficiency declines under high temperatures, dust accumulation, or prolonged exposure to moisture [15–21]. Another major concern is energy storage, which becomes essential due to the intermittent nature of renewable sources like solar and wind. This intermittency strongly influences economic viability because storage systems often represent a large share of the overall microgrid cost, and higher variability in generation requires greater storage capacity. To address this, microgrids frequently integrate fast ramping and cost-effective options such as natural gas to stabilize supply. A summary of commonly used generation sources in microgrids is provided in Table 1.

Table 1. Common microgrid generation sources.

Characteristics	Solar	Wind	Micro-Hydro	Diesel	CHP
Availability	Dependent on geographical location	Dependent on geographical location	Dependent on geographical location	Anytime	Dependent on source.
Output Power	DC	AC	AC	AC	AC
Control	Uncontrollable	Uncontrollable	Uncontrollable	Controllable	Dependent on source.
Typical interface	Power electronic converter (DC–DC–AC)	Power electronic converter (AC–DC–AC)	Synchronous of induction generator	None	Synchronous generator.
Power flow control	Maximum Power Point Tracker and DC link voltage control	MPPT, pitch and link voltage control	Controllable	Controllable	Automatic Voltage Regulation and governor.

Source: ADB.
Note: AC = alternating current, CHP = combined heat and power, DC = direct current, MPPT = maximum power point tracker.

A grid-connected microgrid relies on five main types of components: local power generation, energy storage units, consumer loads, connection to the utility grid, and a dedicated control system. The choice of equipment within these categories depends on the ability of the microgrid to balance supply and demand through smart management of fluctuations [22–25]. When designing such a system, factors such as reliability, cost-effectiveness, environmental sustainability, and the characteristics and accessibility of the local grid are central considerations. A microgrid generally functions in two primary steady states: grid-connected mode and island mode. In addition, it experiences two transient states that occur during the transition between these modes of operation. During all these four conditions it must remain stable and maintain grid code requirement.

- Additional hardware and software are required to control the voltage power and flow in the aggregate system to produce the improved behavior required of a microgrid.
- The connection interface (CI) to the utility network is something like a circuit breaker, although solid-state switches and back-to-back power electronic inverter.
- The selection number shown in Figures 1 and 2 as the energy absorption and injection capability

is usually required to balance power flows at the onset of Microgrid islanding.
- Energy storage could also be used to control the net power flows to and from the utility in the grid-connected mode, allowing the Microgrid to behave as a “model” citizen, capable of assisting stable network operation by providing improved power quality and voltage control.

Advantages of Microgrid
- Ability to disconnect from utility grid during disturbance and operate independently.
- It reduces demand for utility grids and thus prevents grid failure.
- Both electricity and heat energy can be used so that overall efficiency increases.

Disadvantages of Microgrid
- Voltage, frequency and power quality should be at acceptable limits.
- Requires battery tanks to store, which require space and maintenance.
- Resynchronization to utility grid is difficult.
- Protection is difficult.

The challenges related to the control and operations of microgrids are very high. Microgrids are required to ensure reliable operations even at fault conditions, power system stability during disturbances, and power quality in the island mode. The grid connected microgrid is needed to maintain synchronism at any situation [26–28]. Microgrids need to have advanced control strategies for microgrid inverters to maintain correct frequency and voltage to ensure stable operations for the power system connected with dynamically variable load. The growth of microgrids and their challenges have gained attention of researchers and various government and private organizations to play a vital role in finding out the solutions of effective implementation of microgrid. One of the major problems in microgrid is protection system in main grid and microgrid faults [29–33]. When there is any fault in main grid protection, microgrid needs to be isolated immediately, and similarly if there is any fault in microgrid, the protection system should isolate the smallest part of the microgrid to clear the fault. The selectivity and sensitivity play a vital role in low voltage microgrid power management. False tripping, unnecessary tripping, delayed tripping, and undetected faults are the major challenges in design of protection system in microgrids [34–38]. The number of installations of distributed energy resources and availability of short-circuit current in the island mode of microgrid are the major issues while considering the protection of microgrids. Compared to main grid, the short-circuit current will drop drastically and will give problems in the protection of microgrid. There is a need for designing a proper protection system for distributed energy resources with short-circuit calculations and placement of over current relays, reverse power relays, and directional over current relays [39–41]. In real time, the operating conditions of microgrid are variable because of intermittent distributed sources and dynamic electrical load demand. This leads to change in network topology frequently to aim to minimize loss, economic load dispatch, and proper unit commitment with satisfying all the constraints. The directions and magnitudes of short circuits will vary because of these situations. The different sizing of equipment in various components of microgrid creates often a loss of relay coordination, and generic over current protection will become ineffective in protection of the microgrid from faults. The invention of new methodology in protection mechanism is very much needed to set different parameters for over current protection, parameters of relays, deal with low short circuit current, and interfacing of power electronic devices with the microsources. Backbone of the microgrid power supply is renewable energy sources. Most used renewable energy sources are fuel cells, microturbines, solar, and wind. Fuel cells can produce power through electrochemical actions among oxygen and hydrogen. This reaction is highly effective and gives bi product as water and temperature [42–46]. Due to this environmentally friendly bi-products, this technology has become popular compared to conventional diesel engines which are more expensive and pollute environment by releasing flue gases. Even though fuel cells are discovered in eighteenth century, they have been in use in late nineteenth century. Because of usage in commercial and domestic applications, fuels cells power technology becomes popular. Fuel cells have more advantages such as power quality, very highly efficient, environment friendly, and modularity. Recent times in microgrid applications, fuel cells are very effective in replacing IC engine usage which makes microgrid environment free. Further fuel cell technology usage will reduce greenhouse gases and improve efficiency of the microgrid. Advancement in fuel cell technology leads to bloom box energy servers which convert fuel into electricity through electrochemical approach. Bloom box servers are available as building boxes as clusters ratings from hundred kilowatts to megawatts. Bloom box is highly efficient in power production, modular, and scalable [47–49]. Wind energy is most promising source of renewable energy source, which has more potential in future. Wind energy power plants are sustainable energy producers. Wind turbines play a vital role in supplying power along with fuel cells and solar cells to microgrids. Wind turbines are bundled into components such as rotor, generator, turbine blades, and driver or a coupling device as shown in Figure 1. As high speed rotates the blades, the air exerts aerodynamic forces which will make the blades turn the wind rotor. In turn, rotor rotates the generator through gear box. Wind generators are mostly induction generators or permanent magnet generators which supply power to the microgrid.

Figure 1. Wind turbine model.

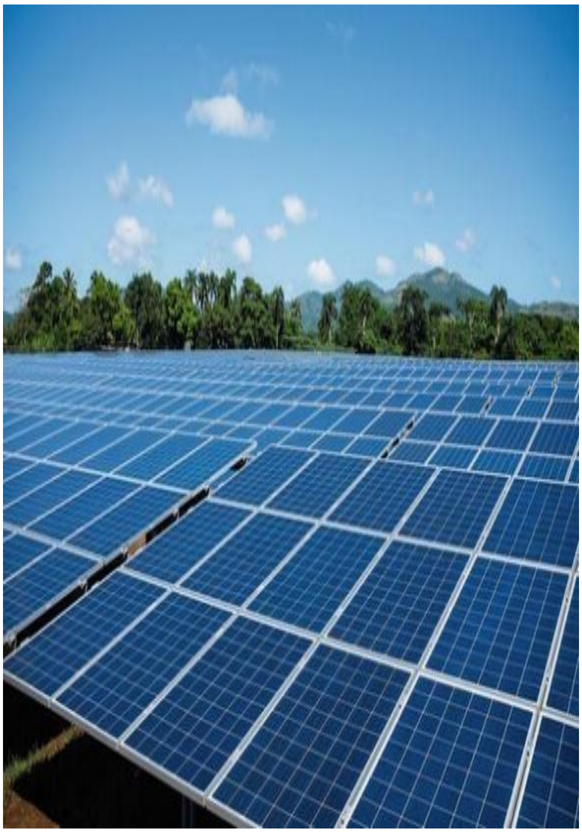


Figure 2. Photovoltaic PV panel model.

Solar power plant generation systems are converting sunlight into electric power either directly using PV cells or indirectly using concentrated solar power plants. Photovoltaic generation is system which converts the sunlight directly to electricity as shown in Figure 2. PV cell technology is very well established and used extensively in microgrid [50–53]. The DC output of the connected PV cells is given as input to the inverter and AC power supply given to the load through inverter. The most common renewable energy source in the world is solar energy. All microgrids are effective in extracting local energy source from solar sources. The main advantages of these solar power plants are very less time required to design and install the power plant. These plants are highly modular, and it is good alternative for peak load demand. Since solar structures are static and have no moving parts which gives no noise power plant status to solar power plants. Solar power plants are portable and mobile because of light weight. Since there is no moving part, PV generation systems are having longer lifetime which makes one of the attractive renewable energy sources connected with microgrid. Microturbines and micro-hydroturbines are gas and hydroelectric generators ranging in size from 25 to 500 KW connected with microgrid [54]. These microturbines are very useful in dealing with peak load demands for microgrids. Biomass is also another renewable source contributing energy supply to microgrids located in remote villages or urban waste sources. The source materials are scrap lumper, forest debris, certain crops or manure, etc. Geothermal power plants are recent renewable energy sources generating power from geothermal energy. Geothermal energy is a thermal energy stored in the earth that is utilized. In future, microgrids are expected to add mini geothermal power plants in their pool of distributed energy resources. In future, the other renewable energy power supply from tides of the sea and hot hydrogen fusion will be a part of microgrid energy sources.

MICROGRID TYPES BY DESIGN ARCHITECTURE

One approach to classifying microgrids is based on their operational control, which is either centralized or decentralized. In a centralized microgrid system, a single entity, the microgrid central controller (MCC) is responsible for the decision-making processes essentially determining the setpoints of the loads, distributed generation resources, and storage units. The MCC communicates with the converters to control the active and reactive power input from the DERs and circuit breakers to control the connection of loads, DERs, and microgrid to the rest of the system. Wireless communication technologies are usually used for data transmission [55–57]. This architecture is a suitable option when all actors in the microgrid has common goals. As an analogy, in the traditional electric grid, centralized control is generally performed by a single entity at the transmission system operator level. Similarly, in the case of a microgrid, when applying centralized control, a single entity carries out the economic dispatch and the unit commitment calculations. The setpoints are provided to the distributed sources by an MCC (as would have been by the distribution system operator in the traditional electric grid). An MCC can be managed by the distribution system operator or by a dedicated microgrid operator, depending on the ownership structure shown in Figure 3.

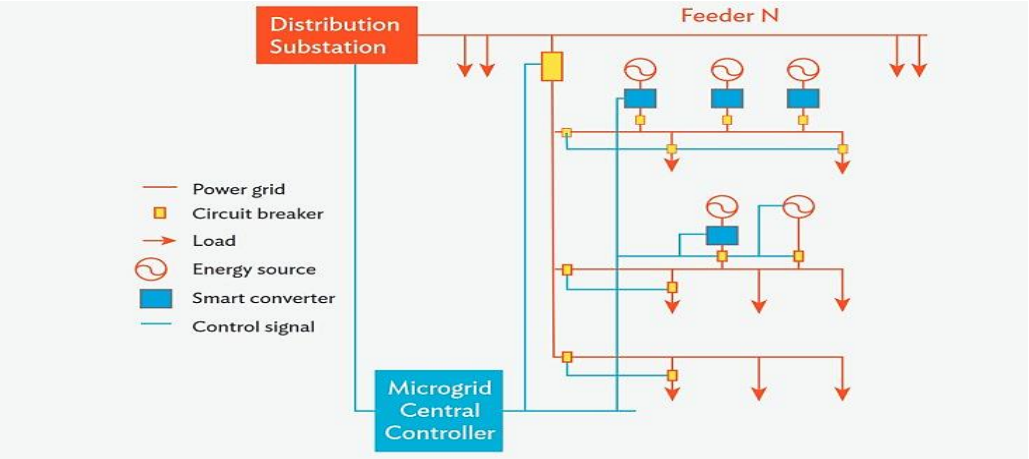
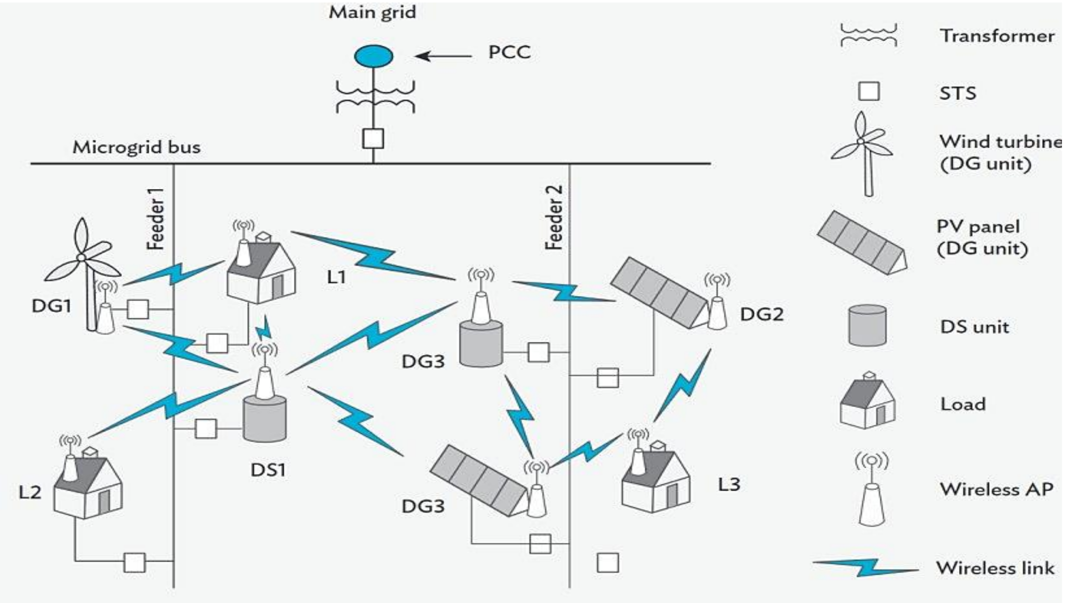


Figure 3. Design architecture of microgrid.

In a decentralized microgrid system, the internal microgrid control takes place at each controllable element in the microgrid generators, storage, and loads. It does not require a powerful central controller and is resistant to single point of failure. Negotiation among the different actors may take place, especially because in this case, the different actors have different goals, but common aspects and calculations, like load forecasting, state estimation, and security monitoring, can still be done in a centralized manner. The performance of the control algorithms depends on four key attributes:

- The number of nodes. The DG and controllable loads that make up the microgrid affect the complexity and computational time as the number increases.
- The number of messages exchanged. The DG and loads in microgrids are usually dispersed, and the communication systems at low voltage usually have limited bandwidth. In several cases, the number of messages required to perform a task is of primary importance. A decentralized control approach reduces the number of messages, as only a small part of the information needs to be transferred to the higher levels of the control hierarchy [58].
- The size and structure of the system model. The structure and complexity of the system need to be considered. Decisions taken by different actors might not only increase the number of nodes but also impose extra technical and nontechnical constraints.
- The accuracy and optimality of the solution. The convergence and accuracy of the solutions depend on the type and accuracy of the algorithms used, and the input data.



AP = access point, DG = distributed generation, DS = distributed energy storage, L = load, PCC = point of common coupling, PV = photovoltaic, STS = static transfer switch.

Source: George, S. and S. Chauhan. 2015. An Investigation into Centralized and Decentralized Micro-Grid Systems with Synchronization Capability and Flywheel. *International Journal of Enhanced Research in Science Technology & Engineering*. 4(5). pp. 225–248. https://pdfs.semanticscholar.org/068b/ e24d624ddfe09e4043deeac2ea72c6655499.pdf. .

Figure 4. Centralized control of microgrid.

Advantages of Centralized over Decentralized Centralized control schemes shown in Figure 4 have the following advantages:

- They provide a high level of operational knowledge, where the main goals are clearly identified and achieved.
- They can provide global optimal solutions.
- They allow easy synchronization to the main grid, and they can effectively use real-time signals for online operation.
- Decentralized control schemes have the main disadvantage of being very complex with respect to multi-ownership and competition between the various actors or agents. Each agent seeks to achieve its own objective, such as maximizing its profits.

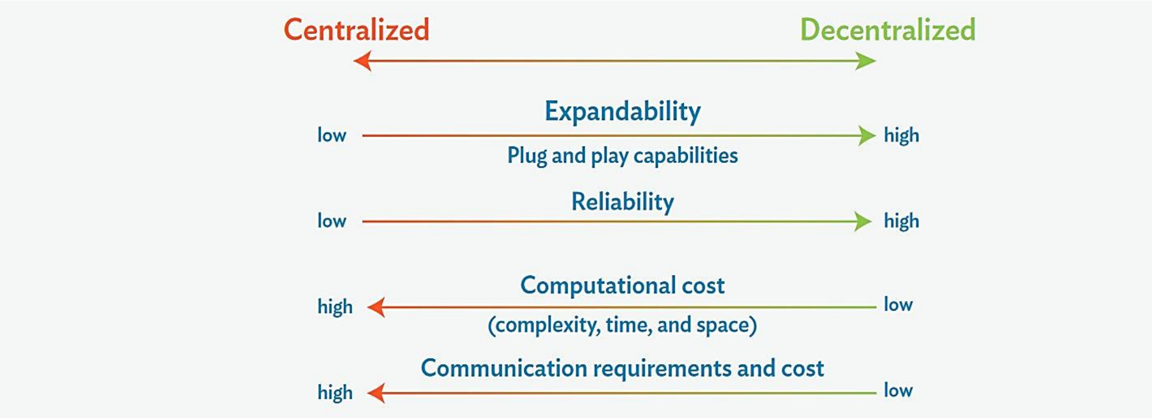
Source: Elizondo, L.R., ed. 2018. *Solar Energy: Integration of Photovoltaic Systems in Microgrids*. Delft: Delft University of Technology (TU Delft). https://ocw.tudelft.nl/courses/solar-energy-integration-photovoltaic-systems-microgrids/.

Figure 5. Decentralized control of microgrid.

Advantages of Decentralized over Centralized Decentralized control schemes in Figure 5 have following important advantages:

- They are suitable for fast changing infrastructures. They could easily be expanded because of their plug-and-play capabilities.
- They are reliable.

The main disadvantages of centralized control schemes are that they are computationally expensive and time-consuming. The central controller needs to run an optimization problem that considers many distributed generation units, loads, and storage units. The central controller has high communication requirements leading to additional costs and the risk of single point of failure.



Source: Elizondo, L.R., ed. 2018. *Solar Energy: Integration of Photovoltaic Systems in Microgrids*. Delft: Delft University of Technology (TU Delft). https://ocw.tudelft.nl/courses/solar-energy-integration-photovoltaic-systems-microgrids/.

Figure 6. Decentralized centralized control of microgrid with MCC.

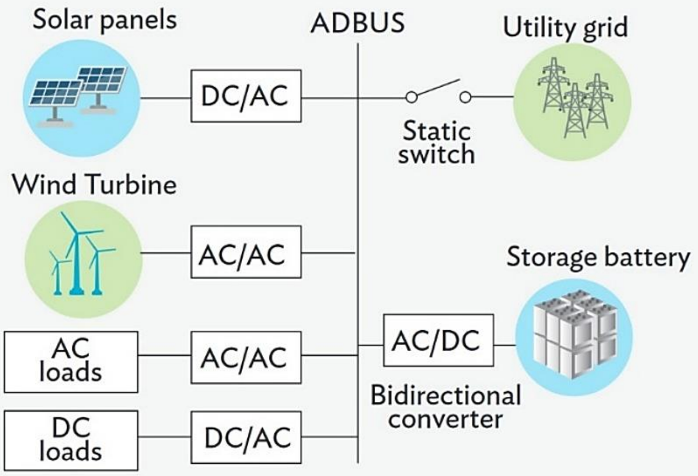
In summary, in centralized control, the microgrid's operation is optimized by a single entity, the MCC in Figure 6, which assigns the setpoints to the loads, distributed generation, and storage units, toward attaining the microgrid's operating strategy and targets. In decentralized control, the decisions are taken locally by the various actors (loads, distributed generation, and storage units) and negotiations may take place, as these actors might have different goals.

Categorized by Type of Power Technology – Alternating Current vs. Direct Current vs. Hybrid

Microgrids can also be classified based on the type of power distribution technology used, AC, DC, or hybrid. While several considerations go into the eventual selection of a power technology for the microgrid, the most suitable option is likely to be an AC microgrid because it needs minimal modifications on the existing installations [58]. However, DC or hybrid microgrids often have better performance and should be considered for new installation greenfield microgrids. As of existing installations, AC microgrid technologies dominate when it comes to integration of local power generation and consumption for both on-grid and off-grid applications, but as DC microgrid technologies develop further, there is likeliness of greater adoption as well combinations of the two approaches, or hybrid configurations.

AC Microgrid

In an AC microgrid in Figure 7, all the DER (renewable and non-renewable), energy storage devices and end-use loads (both AC and DC) are connected to a common AC bus (backbone network). When the microgrid's energy generation exceeds all the loads on it, the microgrid can send out (export) energy to the utility power grid, or charge its energy storage devices, such as batteries, via a bidirectional AC/DC converter. On the other hand, if the loads on the microgrid exceed its internal generation, the microgrid can either take energy from the utility grid or from its own charged energy storage sources [59–61]. This is the grid-connected (normal) mode of operation. However, when a fault occurs on the utility grid and the load demands are not met, the microgrid disconnects itself from the utility grid at the PCC and begins to function in island mode. The merits of AC microgrids include its adaptability that makes it easier to be integrated with the original AC power infrastructure, and the simplicity of its voltage transformation. Also, the AC microgrid equipment costs less compared to DC microgrids. AC microgrids are a feasible option for both cities and rural areas. If disturbances or faults occur, reliable power can be generated in isolated mode. Consequently, as of today, the number of AC microgrids far exceeds that of DC microgrids.



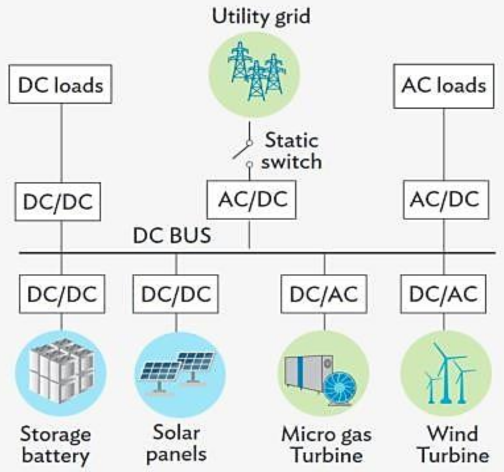
AC = alternating current, DC = direct current.

Source: Anam, F., A. A. Sahito, and A. Shah. 2018. *Comparison of AC and DC Microgrid Considering Solar-Wind Hybrid Renewable Energy System. Engineering Science and Technology International Research Journal.* 2(1). pp. 33–38. http://www.estirj.com/Volume.1/6Faiza21.pdf.

Figure 7. AC microgrid.

DC Microgrid

The operating principle of a DC microgrid is like an AC microgrid, but it is connected to a DC bus. Like AC microgrids, DC microgrids can also be operated in grid-connected or isolated modes. Although it typically has a higher capital cost, the operating costs and system losses are usually lower due to direct connection to DC loads via single stage power conversion [62–65]. DC microgrids are likely to see increased popularity in the coming years as it gives several operational advantages over AC microgrids. In DC microgrids, the generation and distribution system comprise mostly PV units, wind turbines, fuel cells, and other renewable energy sources used to meet energy demands. From its storage devices, it utilizes the DC output voltage, and voltage regulation is better. As there is no need for frequency control, additional system synchronization is not required as shown in Figure 8.



AC = alternating current, DC = direct current.

Note: **A hybrid AC/DC**. Hybrid microgrid is a combination of both AC and DC microgrid, bidirectional converters, and control equipment. Hybrid AC/DC microgrids offer the best solution for grid integration of different DER. A hybrid AC/DC microgrid has minimal conversion losses.

Source: Anam, F., A. A. Sahito, and A. Shah. 2018. *Comparison of AC and DC Microgrid Considering Solar-Wind Hybrid Renewable Energy System. Engineering Science and Technology International Research Journal.* 2(1). pp. 33–38. http://www.estirj.com/Volume.1/6Faiza21.pdf.

Figure 8. DC microgrid.

Hybrid Microgrid

A hybrid microgrid, as illustrated in Figures 9 and 10, integrates both renewable and conventional energy sources, which are connected to end users and managed through control systems to optimize power utilization and storage. Such a system can operate independently in an "islanded" mode or remain connected to the main utility grid, providing support during grid disturbances or curtailments. The specific energy mix within the microgrid depends on the locally available renewable resources, such as solar radiation, wind potential, geothermal energy, or hydropower [66–69].

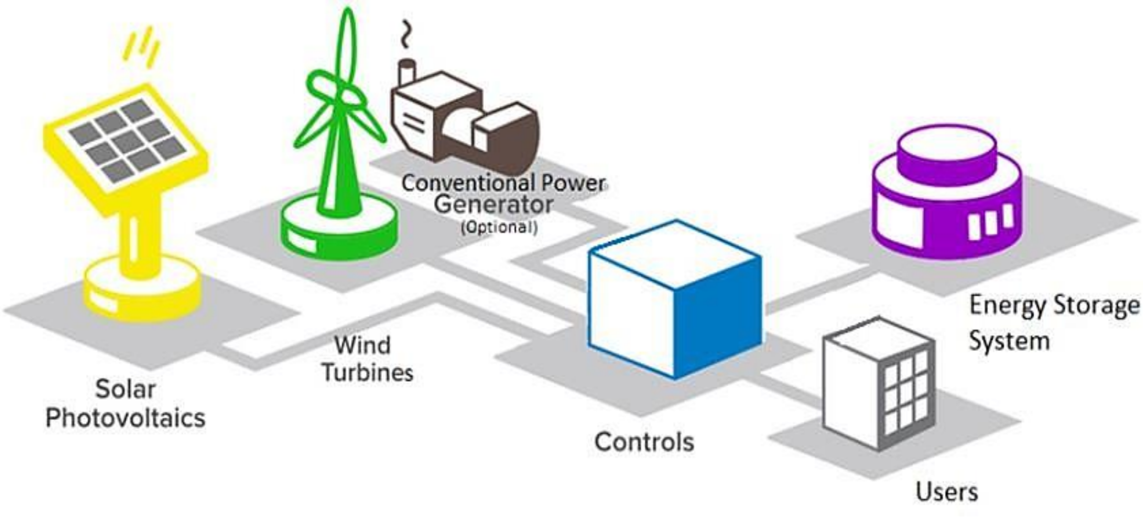


Figure 9. Hybrid microgrid.

A hybrid microgrid, as illustrated in Figures 9 and 10, integrates both renewable and conventional energy sources to deliver power to end users. These systems are managed through advanced control mechanisms that optimize energy utilization and storage. A microgrid can function independently in “islanded” mode or remain connected to the main utility grid, providing backup support during outages, curtailments, or instability in the central network. The specific energy mix of such a system depends on the local availability of renewable resources such as solar radiation, wind speed, geothermal energy, or hydropower [70]. A hybrid microgrid is an advanced form of microgrid that brings together different energy generation and storage technologies to deliver a stable and dependable power supply. In contrast to conventional microgrids, which often depend on a single energy source such as solar panels or diesel generators, hybrid microgrids integrate two or more energy options. This combination allows them to improve overall efficiency, strengthen energy security, and lower reliance on fossil fuels. Below is an outline of the major components and advantages of hybrid microgrids.

Components of a Hybrid Microgrid

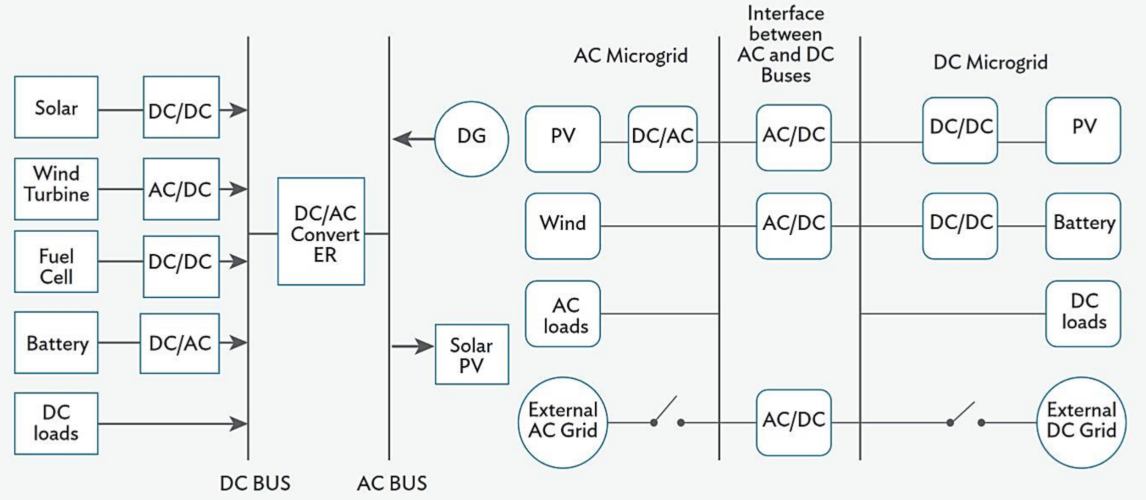
- *Renewable Energy Sources:* Hybrid microgrids usually integrate renewable energy technologies like solar PV systems, wind turbines, and small-scale hydro generators. By utilizing these natural energy resources, they produce electricity in an eco-friendly manner, helping to lower greenhouse gas emissions and decrease dependence on traditional fossil fuels.
- *Conventional Generation:* Along with renewable sources, hybrid microgrids can also integrate conventional units like diesel or natural gas generators. These units act as backup power supplies, maintaining system reliability during times of low renewable output or increased energy demand [71].
- *Energy Storage Systems:* Energy storage systems, including technologies like batteries and flywheels, play a vital role in hybrid microgrids. They capture surplus energy during times of high renewable output or reduced consumption and release it during demand peaks or low generation periods. This process helps balance supply with demand while improving the overall stability and reliability of the grid.
- *Power Electronics and Control Systems:* The integration of advanced power electronics and intelligent control systems play a vital role in the efficient management of hybrid microgrids. They enhance energy utilization, maintain a balance between generation and load, and enable smooth switching between grid-connected and standalone operating modes.
- *Grid Interconnection:* Hybrid microgrids have the capability to function either in a grid-connected mode, where they interact with the main utility network, or in an island mode, operating independently during power outages or emergency situations. When connected to the grid, they can supply surplus energy back to the utility or draw electricity as required.

Benefits of Hybrid Microgrids

- *Increased Reliability:* Hybrid microgrids, which integrate various energy sources and storage systems, improve the reliability and resilience of power supply. They can maintain electricity during interruptions or outages, minimizing downtime and limiting economic impacts for essential facilities and local communities [72].
- *Optimized Energy Management:* Hybrid microgrids enhance energy management by continuously adjusting the balance between supply and demand. They prioritize renewable energy when it is accessible and utilize stored energy or traditional generation sources as required, thereby increasing renewable energy utilization and reducing dependence on fossil fuels.
- *Reduced Environmental Impact:* Hybrid microgrids lower environmental impact and greenhouse gas emissions by combining renewable energy sources and decreasing reliance on fossil fuels. They play a key role in advancing sustainability and addressing climate change challenges.
- *Cost Savings:* Hybrid microgrids can lead to cost savings by reducing fuel costs, minimizing grid electricity purchases, and avoiding penalties associated with peak demand. They offer long-term economic benefits through improved energy efficiency and optimized operation.
- *Energy Independence:* Hybrid microgrids provide energy independence by enabling communities,

industries, and remote areas to generate their own electricity locally. They reduce dependence on centralized power generation and increase self-sufficiency in energy supply [73].

Overall, hybrid microgrids offer a versatile and sustainable solution for meeting diverse energy needs while enhancing reliability, resilience, and environmental sustainability. They represent a key component of the transition towards a more decentralized, resilient, and renewable energy future.



AC = alternating current, DC = direct current, PV = photovoltaic.

Notes:

1. Both the above schematics depict solar, wind, fuel cell as a source of energy and battery for power storage. The left diagram shows a hybrid single bus system with only DC loads; on the right side diagram is a hybrid two bus power supply system with AC and DC loads.
2. AC, DC, and hybrid microgrids each have distinct features, merits, and demerits (Table 5).

Source: Figures taken from Anam, F., A. A. Sahito, and A. Shah. 2018. Comparison of AC and DC Microgrid Considering Solar-Wind Hybrid Renewable Energy System. *Engineering Science and Technology International Research Journal*. 2(1). pp. 33–38. http://www.estirj.com/Volume.1/6Faiza21.pdf.

Figure 10. Hybrid microgrid model.

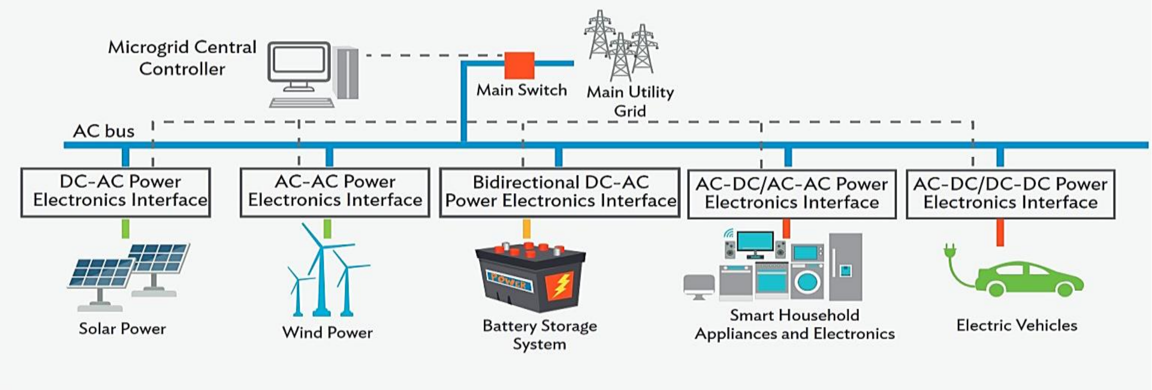
Features of Microgrid Types (Alternating Current, Direct Current, and Hybrid)

This outlines the distinguishing features of different microgrid types, namely Alternating Current (AC), Direct Current (DC), and Hybrid configurations. Each microgrid type offers unique characteristics and benefits, catering to specific operational requirements and application scenarios. Extensive research has elucidated the strengths and limitations of each type, facilitating informed decision-making in microgrid design and deployment.

POWER ELECTRONICS INTERFACE AND DESIGN FOR MICROGRID DC AND AC SOURCES

Power electronics interfaces are used to connect and manage the various components within a microgrid, e.g., generators to loads to storage. Different conversion steps such as direct current (DC) alternating current (AC), AC–DC or DC–DC may be needed to match the input and output voltages of a single component to a microgrid voltage shown in Figure 11.

Microgrids create new opportunities for demand response (DR) by enabling control beyond just flexible loads. They can integrate dispatchable onsite generators and energy storage systems; all coordinated through a microgrid monitoring and control system (MMCS). This integration allows for simultaneous actions such as reducing or disconnecting nonessential loads, activating controllable generation, and utilizing stored energy. Such coordinated operation can enhance participation in DR programs and take advantage of market opportunities, such as time-of-use (ToU) pricing in regional electricity markets. Consequently, microgrids offer a platform for advanced, price-driven, and coordinated responses that can optimize a broader array of assets through demand-side management (DSM) and DR strategies. From a different angle, demand response (DR) can be applied within a microgrid to encourage “rational” operation of flexible end-use devices, prompting them to consume electricity when internal generation is more cost-effective, thereby reducing reliance on the utility grid. Within a microgrid, DR can be implemented at a finer resolution compared to conventional regional grids or independent system operators (ISOs). This is achievable through microgrid management and control systems (MMCS), which can also serve as the demand response automation system (DRAS), managing various facilities via energy management systems (EMS), building management systems (BMS), or directly controlled end-use devices. An additional benefit is that microgrids – particularly commercial, industrial, or campus setups – contain controllable generation, storage, and consumption assets within a confined environment, making control simpler and mitigating many cybersecurity risks.



AC = alternating current, DC = direct current.

Source: Sabzehgar, R. 2017. Overview of Technical Challenges, Available Technologies, and Ongoing Developments of AC/DC Microgrids. In W.P. Cao, and J. Yang, *Development and Integration of Microgrids*. doi:10.5772/ intechopen.69400.

Figure 11. Microgrid DC and AC sources.

Converter Control Techniques

A power amplification system known as a power converter is used in the variable speed wind system to adjust the frequency and voltage of the generator to the grid. Most suggested converters require line filters and transformers to improve power quality and step up voltage levels, respectively.

Back-to-Back Converters

Several types of power converters are created by wind power electronics manufacturers for energy systems, as shown in Figure 12 attached below. Two identical power converter units are commonly used in the arrangement of one of these power converters connected back-to-back (BTB) on the two sides of a conventional DC connection, namely the generator side and the grid side. The BTB converter configurations can be employed in all commercial WECS as shown in the above Figure 11. This configuration was kept back to the back of a connected converter by the two-way power flow from variable voltages/frequency (generator side output) to fixed voltages/frequency (grid side output) and the other way around.

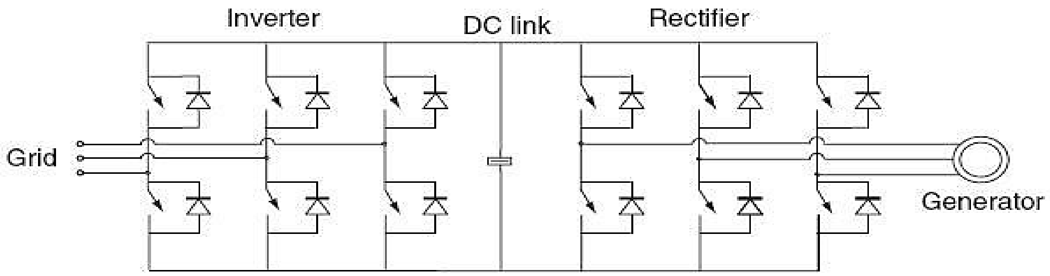


Figure 12. BTB converter.

The simplest sort of power electronics controller is the back-to-back converter control approach, which actively transforms pulsing DC into fixed DC for grid side converters. When in use, the capacitor DC link eliminates undesired harmonics in a steady manner.

Resonant Converters

Resonant series, parallel, and non-parallel resonant tank combinations are depicted below in Figure 13. Both series and parallel setups benefit from the parallel serial LCC resonant converter. The power output of WECS is reduced as the wind speed increases. As the CSI actively manages the DC-link voltage, the charge reduces in terms of DC-link output. Due to a growing input voltage, the device requires more gain as the wind speed lowers. The LCC resonant converter feature satisfies these WECS criteria inherently.

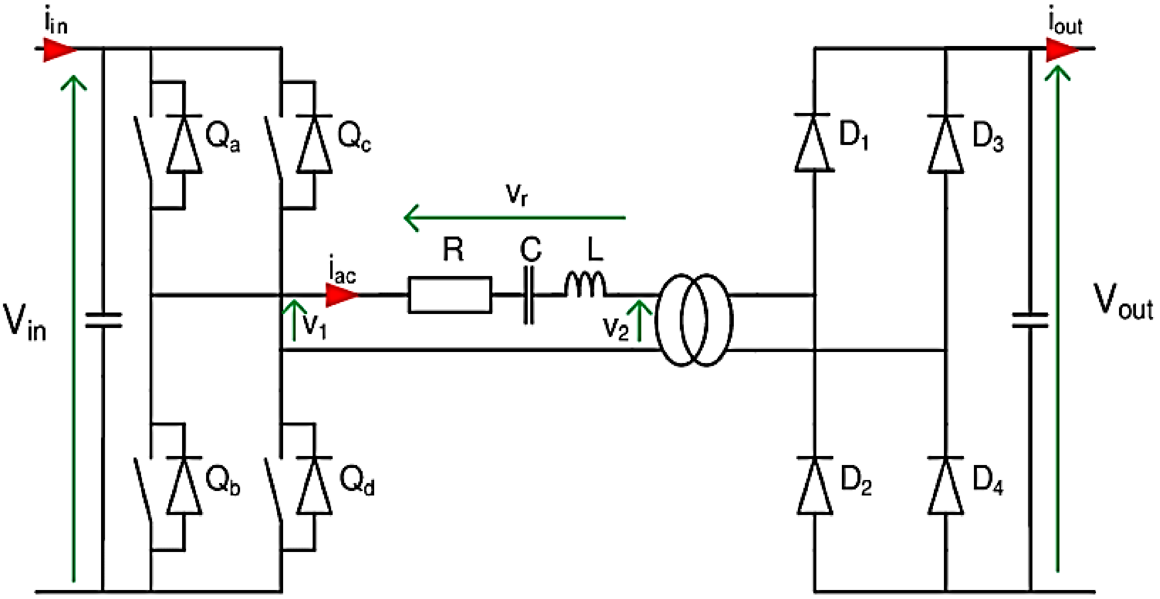


Figure 13. Resonant converter.

The WECS produces a high return despite its low power output, low speed, and low input voltage. The higher converter voltage and parallel (and LLC) resonant converters, on the other hand, lowers the DC gain when the service cycle is performed at a high speed. This unfavorable property causes the semiconductor to be subjected to a great deal of electric stress.

Multilevel Converters

The multilevel inverter works on the principle that a stepped waveform with several steps can approximate sine waveforms. A succession of linked batteries or condensers from various DC stages aids the measures. When the number of levels is raised, multi-level inverters become more complicated to build. However, the control action for converting pulsating DC to fixed DC for grid side converters is extremely fast and total harmonics distortion is less than 5%. Several freewheeling capacitor diodes and capacitor banks are used to keep total harmonic distortion at a reasonable level. When in use, the capacitor DC link eliminates undesired harmonics in a steady manner.

Figure 14 shows a particular multi-level inverter setup that allows for high voltages and hence the operation of a lower voltage rating system. As the number of levels increases, the synthesized output waveform becomes more complex, resulting in a fine stair-like wave that nearly resembles the intended sine wave. Because motor measurements are included in the waveform, the harmonic distortion of the wave’s outcome reduces, approaching zero as the number of rates approaches infinity. Multilevel inverters are, therefore, a superior alternative for high power output since they allow for high voltage amplifier levels without the problems of high dv/dt and other associated inverters.

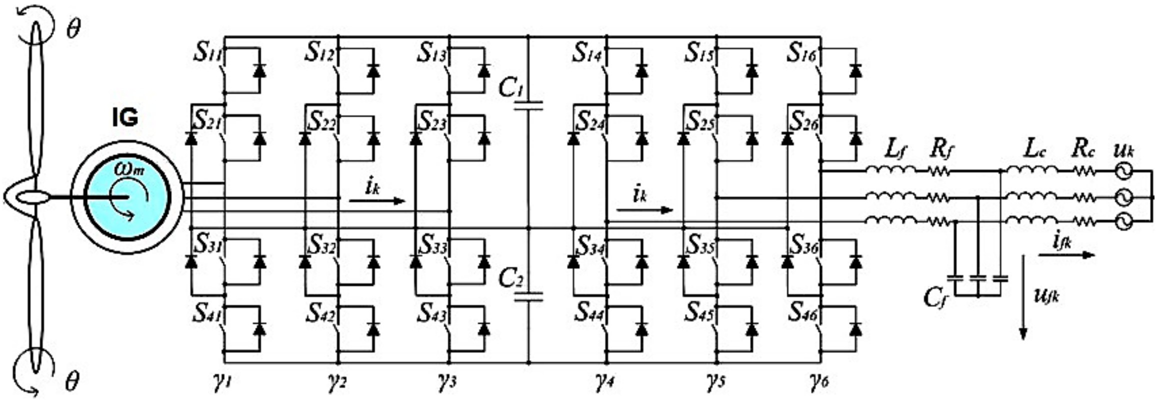


Figure 14. Wind energy multilevel converter.

Matrix Converters

The matrix converter is a forced type switched converter that creates an unregulated frequency changeable output voltage system by using a set of regulated two-way switches as main power elements. It does not require a DC-link circuit or other large energy storage devices. The traditional matrix converter topology (MCT) is made up of nine bi-directional switches that connect each input and output phase. By correctly manipulating the switches in the matrix converter, one can adjust the output voltage size, frequency, and phase angle, as well as the input angle. Matrix is a two-way electricity flow system that can generate high-quality input and output waveforms. Matrix Converters offer unique advantages compared to traditional converters, such as direct AC–AC conversion without intermediate DC stages, leading to higher efficiency and reduced component count. Matrix Converters hold promises for enhancing energy efficiency, grid stability, and power quality in modern electrical networks.

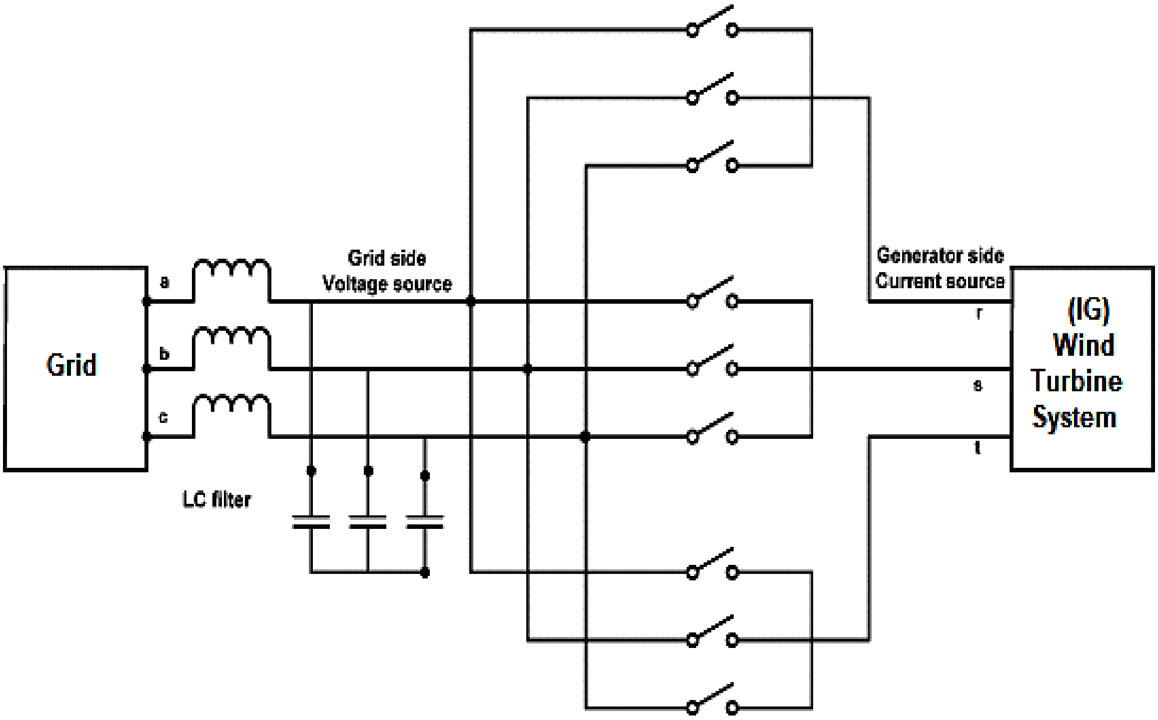


Figure 15. Matrix converter (traditional).

The typical matrix converter schematic diagram is shown in Figure 15. The improved matrix converter is controlled by the same “fictitious DC link” idea as the standard matrix converter. However, there is no power storage element between the line-side and load-side converters. The switches have solved the difficulty of switching.

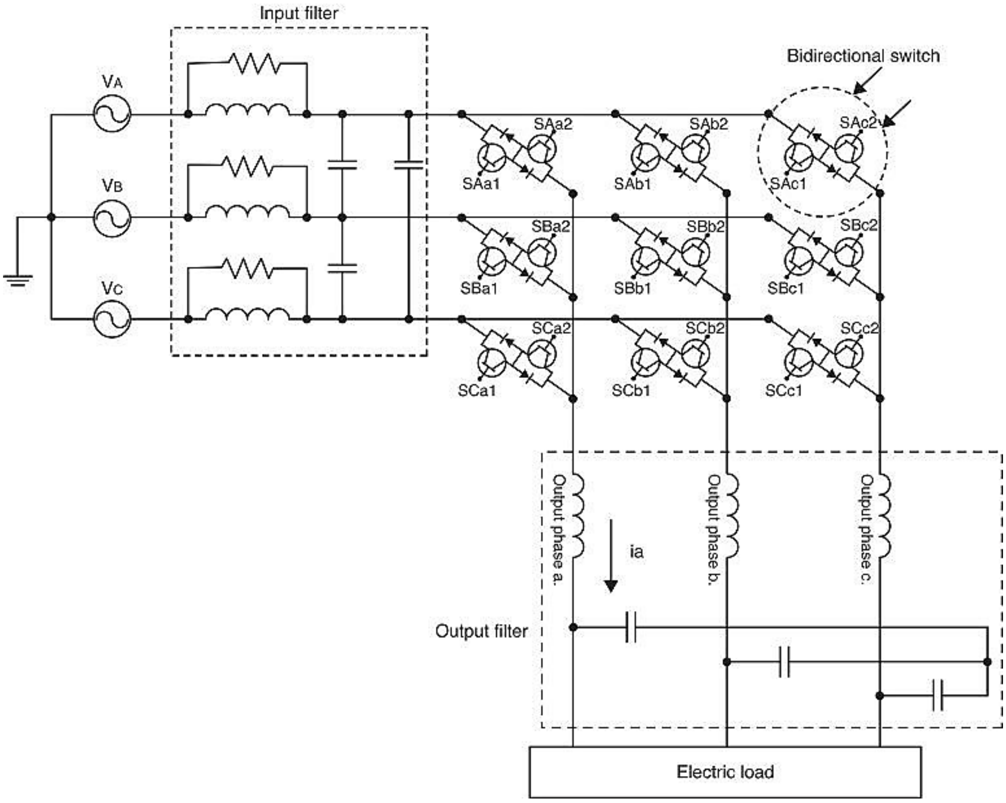


Figure 16. Advanced Matrix Converter.

The line-side has all the twists on and off at zero current. The matrix converter provides four levels of control for managing the magnitude, frequency, and phase angle of input and output voltage, as shown in Figure 16. The above model was constructed in MATLAB/Simulink and shows the converter and inverter parts in Matrix Converter.

Tandem Converters

The Tandem converter is made of cheap rough thyristors with active shunt filters. An active source converter is used. The current waveform is smooth, as shown in the image below, thanks to cascaded multilayer inverters.

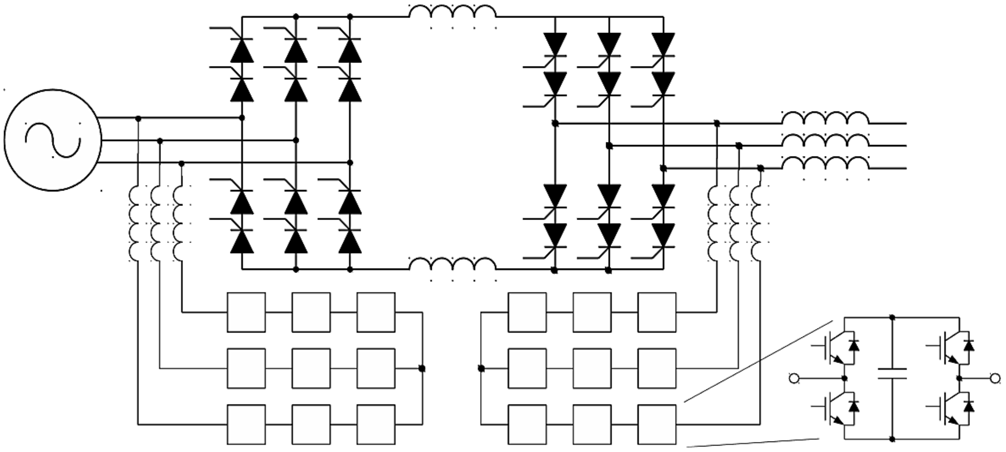


Figure 17. Tandem converter.

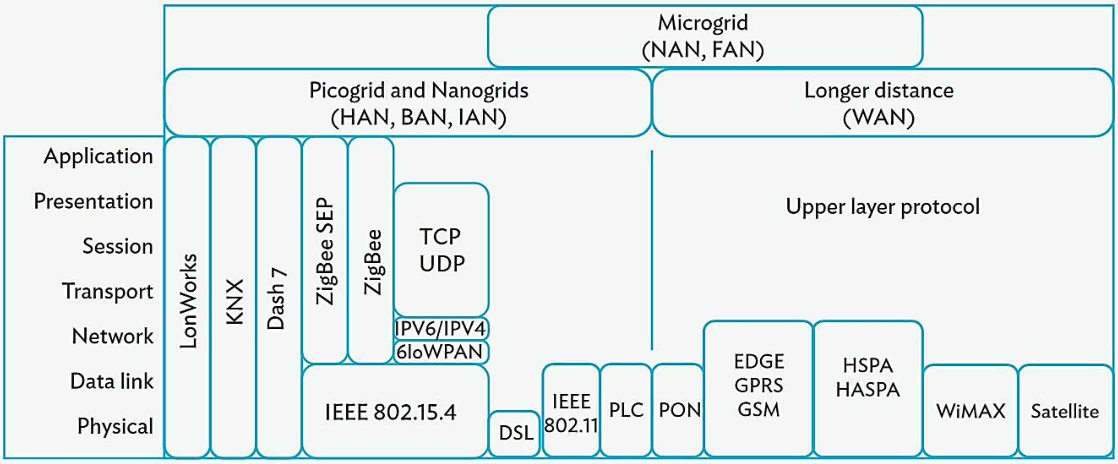
In a tandem converter, the active filters are typically rated at roughly 25% of the converter power, resulting in a decreased DC-link capacitance demand shown in above Figure 17. Furthermore, the higher (current source converter) CSC current harmonics dominate the filter current waveform, thereby lowering the capacitance criteria. Figure 17 shows the DC-link energy storage needs for an MMC and the proposed tandem converter for a 10% ripple of DC voltage at rated power and 2.5 Hz AC frequency. The DC energy storage for an NPC converter with 1% voltage ripple, for example, is shown; however, the capacitance for such a converter is likely to be governed by the current parameters. Increase the number of serial devices and modules to achieve redundancy for both the CSC and active filters.

PROTECTION AND COORDINATION

Protection is an important element in the design of microgrids. It is needed for the microgrid, as well as for cycle-level controls. It must act almost instantly and be carefully programmed to differentiate between grid-connected and islanded operating modes. In a grid-connected configuration, protection is relatively straightforward due to the presence of high fault currents. In contrast, when operating in islanded mode, fault currents are typically lower because of the involvement of power electronics interfaces within the microgrid. These reduced currents may not be sufficient to trigger conventional overcurrent protection devices. Consequently, an adaptive protection scheme is necessary, capable of dynamically adjusting relay settings in real time to ensure continuous microgrid safety. Another approach involves the use of digital relays integrated with communication networks to safeguard the system. A simpler strategy for handling protection challenges is to design the microgrid so that it automatically switches to island mode in response to a fault before any protective action occurs. Additionally, numerous microgrid parameters such as voltage, frequency, and power quality require constant monitoring. Various monitoring methods have been developed, and multiple vendors offer comprehensive monitoring solutions and devices. Monitoring is simpler in DC microgrids than in AC microgrids. Fewer variables need to be monitored and controlled, as frequency and reactive power issues do not exist. DERs and loads are generally connected to the distribution lines of the microgrid through power converters. They adapt the current and voltage levels of the microgrid to the connected units. Power converters vary by microgrid parameters and type, but in general, power conversion efficiency is higher in DC systems than AC systems and mainly depends on the technology of the primary source and AC/DC load ratios. Microgrid monitoring and control systems (MMCS) tie all the microgrid components together and maintain the real-time balance of generation and load. This control system can follow a centralized or decentralized scheme (Section 1.5). In simple microgrid setups, the control system may consist solely of a governor regulating a diesel generator. In more advanced configurations, the Microgrid Monitoring and Control System (MMCS) integrates sensors, metering devices, advanced software, and communication networks to enable real-time management and optimization of generators, energy storage, loads, and connections to the utility grid. When operating while connected to the main grid, the MMCS must handle the utility interface and exchange information with the utility's operations center or independent system operator, including near real-time coordination with demand response management systems.

Utility Interconnection

A distinctive feature of microgrids is the interconnection with the utility's power grid, sometimes referred to as the PCC. This is what allows microgrids to operate in grid-connected or island modes, and transition is relatively seamless between both. If there is an existing utility interconnection, it lays the foundation for what additional hardware may be needed for the microgrid. This includes elements ranging from existing relays and meters in the substation and distribution equipment, to switchgears and power converters in the microgrid. During grid-connected operation, the microgrid-utility interconnection at the PCC must be designed to allow for safe and reliable parallel and concurrent operation of the microgrid and the utility macrogrid. The existing utility equipment may need to be upgraded to handle the various changes that occur when islanding a microgrid. For reliability and resilience, focused microgrids where relatively frequent island mode operation is anticipated; the PCC must also incorporate equipment to allow for seamless disconnection and reconnection of the microgrid to the power grid. This re-synchronization of the two systems is a complex process and failure to adequately design for this function can result in instability of both the microgrid and the main power grid.



BAN = building area network, DSL = digital subscriber line, FAN = factory area network, GPRS = general packet radio service, GSM = global system for mobile communications, HAN = home area network, HASPA = high speed packet access, HSPA = high speed packet access, IAN = industrial area network, IEEE = Institute of Electrical and Electronics Engineers, NAN = neighborhood area network, PLC = power line communications, PON = passive optical network, TCP = transmission control protocol, UDP = user datagram protocol, WAN = wide area network, WiMAX = worldwide interoperability for microwave access.

Source: Elizondo, L.R., ed. 2018. *Solar Energy: Integration of Photovoltaic Systems in Microgrids.* Delft: Delft University of Technology (TU Delft). https://ocw.tudelft.nl/courses/solar-energy-integration-photovoltaic-systems-microgrids/.

Figure 18. Utility interconnection of microgrids.

Accordingly, islanding of microgrids must be addressed at both technical and policy levels (safety concerns, potential end user equipment damage, reclosing scenarios, inverter prioritization). Effective communication channels are critical for the successful operation of microgrids, as they enable stable, reliable, and efficient performance. The integration of distributed generation and diverse loads, along with the interactions among various nodes, significantly complicates the control and management of the power system, and consequently, the communication requirements. Therefore, the microgrid's communication network must provide highly reliable, bidirectional, and interoperable connectivity between all microgrid components. In essence, the communication system acts as a vital link connecting the physical infrastructure of the microgrid with its control and protection mechanisms. This contrasts with the traditional power grid structure, which typically lacks connectivity, as it is meant to function as a centralized unidirectional system. Systems architecture, standards, and tools are involved in designing how a microgrid will communicate internally using one or more languages or protocols, through wired (fiber, copper) or wireless (radio, cellular) communication pathways, some of which may already exist. Grid-connected microgrids are rarely standalone but interact and communicate with the traditional electric grid on one side and industrial, commercial, institutional, residential, and other end uses on the other, which may contain sub-grids (Figures 18 and 19). Microgrids and these networks they interact with are broadly classified as wide area networks, industry area networks, field area networks, neighborhood area networks, body area networks, and home area networks. The communications technologies and standards used in these applications are shown in Figure 18. Finally, some form of cybersecurity is essential. Given the extensive communication and controls, there is vulnerability to cybersecurity threats wherein a single infected computer can spread a virus on to the network, thereby affecting an entire microgrid. Microgrid operators and individual smart homeowners usually rely on their equipment providers to design a cybersecure microgrid. A global safety consulting and certification company published in July 2017, the first edition of a cybersecurity standard. This was subsequently also published as an American National Standards Institute (ANSI) standard. Adoption of this standard by equipment providers will help improve cybersecurity in microgrids. Components that are more robust, versatile, and durable incur greater up-front costs. However, higher microgrid capital costs can often be justified if the negative repercussions of a customer outage are large (e.g., financial firm data center outage, air traffic control outage, life support system outage, spoiled batch in a semiconductor fabrication process). Accordingly, while the enhanced reliability and resilience provided by more sophisticated microgrids might cost more, it provides value that is often multiples of the additional cost. Therefore, the customer's objective should drive the microgrid's design.

Power Quality Issues and Solutions

At present, the overall penetration rate of renewable energy in China is low. The large-scale access of renewable energy has not fully exposed the impact of the traditional power generation, transmission, transformation and distribution system, and the state has formulated a series of measures to prevent the power grid shock and instability caused by the fluctuation and intermittency of renewable energy, such as the proportion of renewable energy, like photovoltaic and wind power, connected to the power grid should be strictly set; wind power generation base implements wind and thermal power bundling policy, etc. [74]. However, eventually, renewable energy will eventually replace traditional energy, and the penetration rate of renewable energy will continue to increase, which will have a serious impact on the safe and stable operation of the entire power grid.

Influence of Current Distribution

When the penetration rate is low, the output of renewable energy is less than the local load and is completely absorbed. The microgrid is equivalent to a pure energy-consuming load for the traditional grid, and energy always flows unidirectionally from the grid to the load. With the large-scale integration of renewable energy, the penetration rate continues to increase, and when the generated electric energy cannot be absorbed inside the microgrid, the microgrid is no longer a load for the traditional grid, and there is a two-way interaction with the power grid, which makes the traditional power grid change from the single power radiation mode to the multi-power network terminal mode, and affected by factors such as sunshine intensity and wind energy resources, the microgrid operation mode need to change frequently, which makes the power flow distribution of the power grid extremely complicated.

Influence of Voltage

After the microgrid is connected to the power grid, the voltage at the grid connection point and nearby areas is not only affected by factors such as power source, load size and nature, transmission line impedance and distance, but also closely related to the operating status of the microgrid [75]. The output status of distributed power sources such as photovoltaics and wind power are affected by factors such as wind speed, cloud obscuration, time and other factors, which have greater volatility and intermittent. When the penetration rate is low, and the electricity generated by the microgrid is greater than zero and less than the local load, the input power of the large grid to the grid connection point is reduced, which helps to improve the static stable voltage of the distribution network, but the grid connection point voltage will be slightly increased; when the penetration rate is high, the greater the reverse input power of the microgrid, the more easily the voltage at the access point is affected by the output of distributed power sources in the microgrid, resulting in larger waves, and overvoltage may occur [1]. To meet the requirements of different loads, the distributed power sources in the microgrid are often put into or separated from the large power grid, which can easily cause system voltage fluctuation and flicker. In addition, due to the small capacity of the microgrid itself, when its energy reserve is insufficient or the reactive power compensation cannot meet the system requirements, it will also cause voltage fluctuations and flicker [6].

Influence of Frequency

The renewable energy power generation equipment in the microgrid is connected to the power grid (or diesel generator set) through power electronic conversion devices, and most of them do not have the primary frequency regulation capability. When the grid load is reduced, the inverter can maintain the grid voltage and frequency basically remains unchanged and is quickly stabilized by limiting the power to be consistent with the grid, but when the load rate of the power grid increases or the renewable energy output fluctuates greatly due to weather changes, the grid frequency will produce large fluctuations, and the maximum amplitude of the fluctuations is directly related to the penetration rate. In addition, the operating status of renewable energy power generation equipment is affected by the control strategy and energy characteristics of the microgrid, and switching action often occurs, which may cause the frequency to exceed the limit of the grid.

Influence of Harmonics

Harmonics are generated in the power system due to the existence of nonlinear loads. Harmonics have many hazards, such as reducing the transmission capacity of the line, increasing the loss of equipment such as transformers, accelerating the aging and damage of the equipment, causing the malfunction or refusal of the relay protection device, and interfering with the communication equipment and line. The development of microgrid and new energy power generation technology has largely benefited from the development of power electronic devices and technologies. Power electronic devices are typical non-linear loads and have been widely used in microgrids. In the microgrid, most of the renewable energy and energy storage loads are connected to the grid through power electronic converters; in addition to the device itself, the power electronic inverter can also generate harmonic current related to the carrier frequency and the switching frequency of the device in PWM (pulse width modulation) technology. In addition, distributed power sources such as photovoltaics and wind power are connected to the grid, and their output is affected by natural conditions, which are intermittent and fluctuating, and will also inject large fluctuating harmonics/interharmonics into the grid. It will increase the harmonic fluctuation and noise of the whole system [9, 10]. With the increase in penetration rate, the types of electronic and electronic devices and devices have become increasingly complex, making the grid topology and parameters become uncertain, the source and propagation characteristics of harmonics have become more complex, and the interference of harmonic analysis noise has become larger, which increases the difficulty of harmonic recognition and processing.

Influence of Operating Characteristics

In the high-penetration renewable energy microgrid, the intermittent, random and weak support characteristics of renewable energy output such as photovoltaic power generation and wind power generation are more prominent, and the power conversion, control strategy and dynamic characteristics of the distributed power supply based on the power electronic converter interface are quite different from those of the traditional AC synchronous generator, which have a great impact on the operation characteristics of the power grid. The key to the stability of the high penetration microgrid system is the change of active and reactive power injected into the system during operation. Under disturbance action, the output frequency of traditional generators is determined by the rotor speed of the generator and is controlled by a governor; the amplitude of the output voltage is controlled by the excitation control system or adjusted by reactive power compensation. The output voltage and frequency of the power supply based on the power electronic converter interface is not directly related to the primary energy, and it depends on the power flow control strategy of the converter interface [9]. On the other hand, when the distributed power supply based on the power electronic converter interface responds to load fluctuations, it is limited by the energy source and the DC side capacitor energy of the power electronic converter. The inertia is much smaller than that of the traditional rotating electrical machine. The barrier of the converter decouples the wind turbine from the electrical frequency, so that the renewable energy equipment presents a universal zero inertia or weak inertia. Therefore, in the case of large disturbances, for renewable energy that has weak tolerance to sudden changes in frequency and voltage and generally does not participate in the frequency and voltage regulation of the grid, it is prone to chain disconnection, forming a vicious circle, intensifying the sudden change, and causing serious shock damage to the system and even collapse. Finally, photovoltaic wind energy storage and other equipment are connected to the bus through the power electronic interface, which can achieve fast and flexible power control, resulting in large differences in transient time scales between power sources in the microgrid [18]. Therefore, when the microgrid is externally disturbed, there is not only a microsecond-level electromagnetic transient process, but also a millisecond-level electromechanical transient process and a second to minute-level slow dynamic/medium-long-term dynamic process, making the microgrid dynamic characteristics very complicated.

Influence of Relay Protection

The integration of high-penetration renewable energy microgrids into the distribution network has changed the structure and trend of the power grid and has greatly changed the operating characteristics and fault characteristics of the entire system, making the system protection face new challenges. The main reasons include distribution. The output of renewable energy is intermittent and fluctuating, which increases the difficulty of protection setting. There are multiple power sources such as synchronous motor type, asynchronous motor type, and inverter type in the power grid, and their short-circuit currents vary greatly. The protection methods usually used are also different. For example, power electronic devices are limited by withstand voltage and overload capacity, and the short-circuit current is up to twice the rated current, which makes the fault detection method and protection principle based on the increase of current may fail. There are two-way short-circuit currents inside the power grid, and the equivalent power supply capacity on both sides of the fault is quite different. The fault current is related to the equivalent power supply capacity; the microgrid can operate in two modes of islanding and grid-connected, and often switch between these two modes, but the short-circuit current is quite different in these two modes; compared with the traditional power grid, the micro-grid has small capacity, low inertia, and high fault removal time requirements, and the two requirements are inconsistent; due to natural conditions and control strategies, renewable energy needs to switch frequently, so that the topology of the microgrid is also changing during operation. The above situation leads to the mis-operation and rejection of the traditional “three-stage relay protection”, which depends on the over current time limit, and the reliability of the system becomes lower.

Key Technologies of High Penetration Microgrid

Safe and stable operation is the bottleneck for the development of high-penetration renewable energy microgrid systems. To adapt to the development of high-penetration renewable energy, the following key technologies should be focused on research.

Precise Prediction Technology

The root of the impact of renewable energy on the operation of the grid lies in the uncontrollability, intermittent and volatility of energy. If accurate forecasting of renewable energy and grid load can be achieved, the system control strategy and power electronics operating conditions can be adjusted in advance to reduce the impact of renewable energy and grid disturbances on the operating characteristics of the grid. At present, although many studies have been carried out at home and abroad, the overall prediction accuracy is 80% to 90%. To a certain extent, the forecast of the trend of renewable energy power changes, but the prediction of renewable energy fluctuations caused by atmospheric turbulence and cloud cover needs to be further improved in accuracy. In power forecasting, it is necessary to fully integrate economic and meteorological information and use advanced big data processing methods to deeply analyze the changing laws and patterns of renewable energy, grid load, etc. to further improve the prediction accuracy, which is beneficial to the stable operation of power grid.

Reasonable Configuration of Energy Storage Technology

Energy storage equipment is an essential part of the future power grid. Reasonably configure energy storage methods and capacity for high-penetration renewable energy microgrids and give full play to the role of energy storage equipment, which can effectively suppress and smoothen the volatility and intermittency of renewable energy power generation, provide inertial reserves for the system, and improve system power schedulable, reactive voltage support and fault traversal capability. By combining with the grid-connected inverter, it can participate in the frequency and voltage regulation of the whole power grid, so that the anti-disturbance and stability of the power grid can be enhanced.

Demand Side Control Technology

The load on the demand side of the power grid contains many temperature-controlled loads, such as electric water heaters, refrigerators, air conditioners, and charging loads such as electric vehicles. Short-term slight changes in temperature or charging rate (period) will not affect the comfort and function of users, this kind of load is called controllable load or flexible load, this kind of load can participate in microgrid frequency adjustment. In Europe, controllable load accounts for about 30% of all electricity consumption, and this proportion will continue to rise with the increase of electric vehicles. With the development of smart grid technology, grid elements have become fully available, and user load types, capacity, and electricity usage rules have become public. It will be possible to introduce users to the electricity market in the next step, encourage users to participate in power demand response, and realize the participation in the power grid frequency modulation through controllable load regulation, which has the advantages of large capacity, fast response speed and so on, thus improves the adjustment toughness of power grid.

Intelligent Adaptive Relay Protection Technology

Microgrid relay protection must not only achieve the reliability, selectivity, quick-action and sensitivity required by traditional relay protection, but also meet the requirements of adaptability, that is, the same set of protection strategies can adapt to the islanding and grid connection of the microgrid. It runs in two modes, and when the topology of the microgrid changes, the protection strategy will not fail. Microgrid has the characteristics of multiple operation modes and multiple operation state network structure changes, etc. The research mainly focuses on the intelligent algorithm relay protection system suitable for the current characteristics of microgrid, exploring how to effectively identify the network topology structure and operation state changes, and on the basis of fault feature model and real-time measurement data to explore suitable fault current calculation method, automatically adapt to the operation process of micro power grid structure and the change of the mode, automatic adjustment of related parameters of the protection device. Through the integration of multiple protection methods, centralized protection and local protection cooperate with each other, focusing on special design for PCC points, microgrid buses, feeder lines, distributed power sources and loads. In addition, the existing relay protection devices were upgraded by adding intelligent auxiliary modules to meet the protection requirements of high penetration micro-grids.

Modification of Traditional Generator Control Technology

Eventually, renewable energy will surely replace traditional fossil energy, but for a long period of time it must be a deep integration and complementary coexistence between these two. At present, in the face of the impact of the access of renewable energy, the main measures are to increase the redundancy factor of the installed capacity of renewable energy and supporting thermal power units. This will not be a long-term solution. Focusing on traditional thermal power units' peak shaving capacity, climbing speed and start-stop time, etc., upgrading the generator sets can improve the support capacity of the renewable energy power generation system, to enhance the anti-interference and fast recovery performance of the renewable energy connecting to the grid.

Planning & Design and Coordinated Control Technology of High-Penetration Renewable Energy Microgrid

In view of the multi-temporal and spatial distribution characteristics of high-permeability renewable energy and its impact on the grid, the strong intermittent and volatility of renewable energy output, and the large number of controllable load access characteristics, people still need to study the microgrid architecture and composition, distribution network form and structure, distributed power source type and capacity optimization configuration, role and form of energy storage unit, multi-objective and multi time scale control strategy, system optimized operation and energy coordinated control, scientific and effective relay protection system, etc. At the same time, people also need to carry out research on the active reconfiguration and autonomous operation of the distribution system considering the coordination of electric vehicles, energy storage and renewable energy, and the theory of collaborative optimization in the market environment, so as to give full play to the support of energy storage units and controllable loads, so as to reduce the dependence on traditional generating units and realize scientific management and safe and economic operation of high-permeability microgrids.

Microgrid Design, Operation, Maintenance and Energy Storage Systems (ESS)

Once the feasibility study is completed and the project receives a green signal, the aspects to consider in the microgrid system design during subsequent conceptual and detailed engineering stages are listed below and pictured in the flowchart in Figure 20.

Demand Forecasting

- Number of customers.
- Length of circuits.
- Load analysis (e.g., critical, controllable, high efficiency, etc.).

Somewhat challenging will be the case of low-income customers with limited technical and financial resources, hence, estimates and extrapolations may need to be used.

Generation Capacity Sizing

- Generation mix.
- DER sizing and design.
  - Optimal sizing of PV and wind.
  - Nonrenewable generation sizing.

Energy Storage Devices Selection, Combination, and Sizing

- Standby power loss.
  - Storage is primarily needed when the microgrid is islanded.
  - Standby power loss will reduce the efficiency of the microgrid.
- Response time.
  - For seamless transition, response time must be very fast.
  - This is more than just battery response time – communications latency and control functions also play a role.

Technical Design

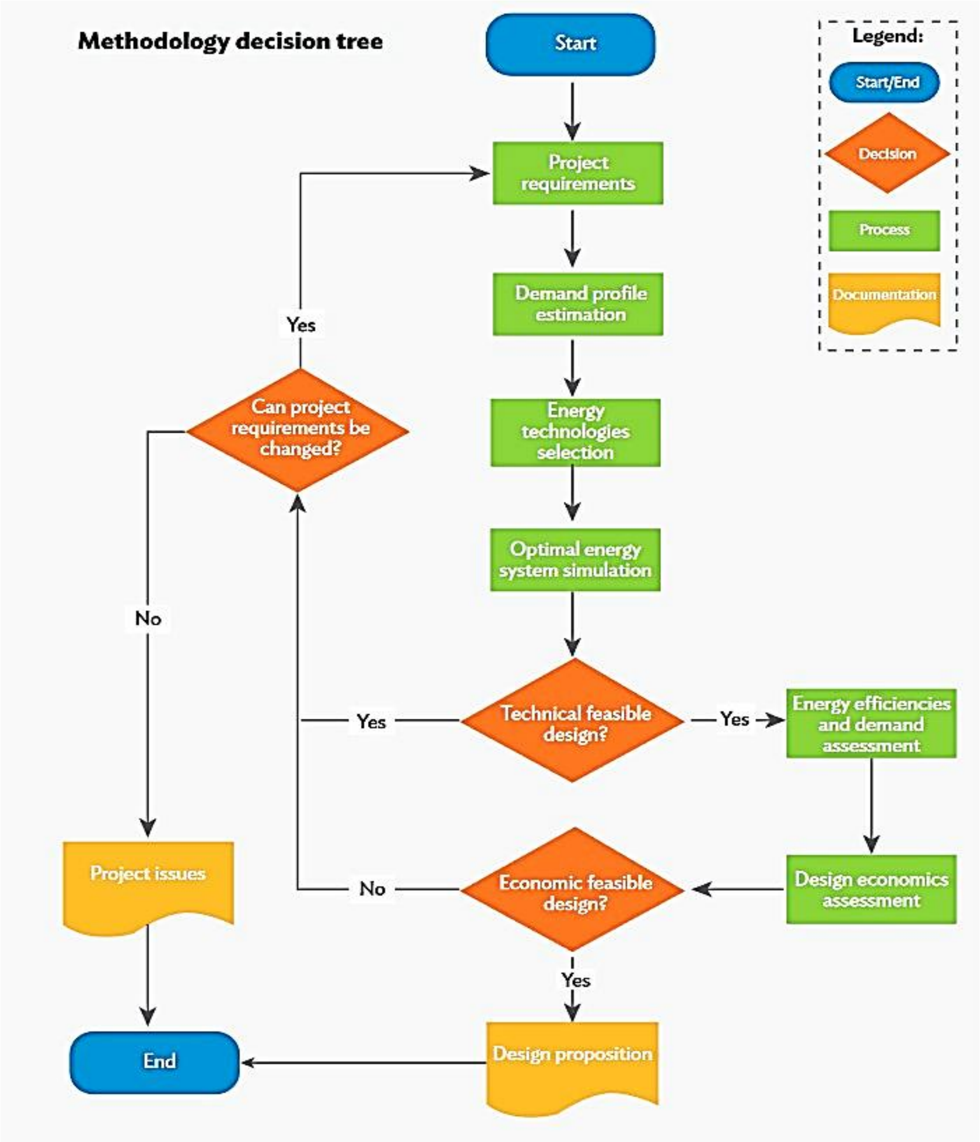
- Microgrid controller architecture and design.
  - Centralized versus decentralized.
- Power technology.
  - AC versus DC versus hybrid microgrids.

- Voltage levels.
- Feeder configuration.
- Desired power quality and reliability levels.
- *Protection Methods:* Several protection schemes have been developed for AC microgrids, both centralized and decentralized. For DC microgrids, this area is less developed because of the lack of standards and guidelines, along with limited practical experience.
- Communications technology.
- Distribution system modeling, simulation, and design.
- Scenarios.
- Model validation.
- Grid impact.

Impact Studies

- Steady state.
- Fault analysis.
- Protection.
- Stability studies.

There are two operating modes for a grid-connected microgrid shown in Figure 20. The normal operating mode is the grid-connected mode. In this operating mode, all the feeders are supplied by the utility or main grid, and the microgrid typically operates this way if there is no power quality disturbance on main grid. However, when there is a fault of other power disturbance on the main grid, the microgrid will be disconnected from it (in a planned or unplanned manner). This is referred to as "islanded" or "isolated" mode of operation. Such transitions, along with maintaining system stability and fault detection are three critical areas for proper microgrid operation. The ability to transfer between grid-connected and islanded modes without any interruptions to the customers is an important function. If certain load and distribution system conditions are foreseen that need to be managed in advance, such seamless transfers can ideally be initiated by the microgrid operator. If a storm warning has been issued, the microgrid operator may decide to transfer the microgrid from grid-connected to island mode operation by simply initiating the sequence via their control system. Once the storm has passed, the microgrid can resume grid-connected operation by seamlessly synchronizing back into the distribution system. In the case of unscheduled events such as distribution system faults, however, there might be brief interruptions in supply to the microgrid's loads depending on the protection system type and setup. In the reverse operation, while reconnecting, the microgrid needs certain information from the grid for synchronization, particularly voltage and frequency setpoints. Proper control mechanisms allow synchronization to occur within seconds, enabling smooth islanding during planned transitions and seamless reconnection, which prevents short interruptions that could impact essential end-user loads.



Source Santos, A. Q. et al. 2018. Framework for Microgrid Design Using Social, Economic, and Technical Analysis. *Energies.* 11: 2832. doi:10.3390/en11102832. https://www.mdpi.com/1996-1073/11/10/2832.

Figure 19. Operating modes for a grid-connected microgrid.

The main power grid dictates the overall system dynamics while in grid-connected mode, due to the much smaller size of microgrids. Thus, the stability analysis of a microgrid in grid-connected mode is like that of the larger power grid to which it is connected. Conversely, in an islanded microgrid operation, the system dynamics are represented by the DGs, the fluctuating output of which, coupled with varying load, may pose challenges to the successful operation of the microgrid. Three levels of supervisory control are typically employed for the reliable operation of a microgrid in grid-connected mode – the distribution level, microgrid level, and local level. The market operator and distribution network operator (DNO) are involved at distribution level. MCC handles microgrid level control, and the unit level control is done by local controllers. At the distribution level, signals are dispatched by DNO and market operator. MCC handles communication between DNO and local controllers to integrate the microgrid with the main grid. When a microgrid functions in grid-connected mode, the utility grid serves as a stable and dependable reference for both voltage and frequency, ensuring the microgrid remains synchronized. The utility is the isochronous generator reference, and all DG and storage resources operate in droop mode. However, when it is islanded from the grid, it needs to rely on its own internal assets to provide this reference to independently support power quality and accommodate any changes to system voltage levels. Many islanded microgrids currently rely on thermal or natural gas generators functioning as synchronous machines to establish an isochronous reference, supply reactive power, and regulate system voltages dynamically. Other sources, such as PV inverters and, in some cases, battery inverters, typically operate in droop mode. A further complication arises in islanded microgrids with a high penetration of renewable energy, which are often entirely inverter-based and do not include any spinning generators. In these systems, intelligent inverters integrated with battery storage are required to manage voltage and frequency control, establishing reference points independently. Additionally, devices, like static compensators (STATCOMs), can be used to provide rapid, continuous voltage regulation in coordination with the inverters.

In simple terms, an electric fault occurs when there is an unusual flow of current in the power system, which can happen for various reasons such as short circuits. Conventional fault detection methods used in utility grids are not directly applicable to microgrids. This is because microgrids feature bi-directional power flows, require the ability to differentiate between grid-connected and islanded modes, and often use converters to connect distributed energy resources (DERs) that supply limited fault current compared to some of the devices and machinery present within the microgrid. Fault detection and design of protection systems are extremely critical areas for microgrids, and currently, there is no standard one-size-fits-all solution. The design and process are typically customized to the individual microgrid with several methods or combinations used including differential protection, communications systems, and advanced signal processing algorithms. As in the case of any other product or system or infrastructure, regular maintenance and upkeep is essential to ensure reliable performance over the effective service life of a microgrid. Fixed costs (e.g., maintenance staff salaries) and variable costs (e.g., direct variable costs that include replacement component costs, and indirect variable costs that include substitute backup generation during maintenance shutdown periods) will be incurred for this. The maintenance strategy and procedures of a microgrid are typically carried out by O&M personnel, based on established protocols and intervals such as periodic general maintenance, scheduled preventive maintenance, and data analytics-based predictive maintenance. Given that there are several different microgrid applications, with varying service requirements and grid connectivity scenarios, there is no one-size-fits-all prescription, and the maintenance costs need to be compared to the cost of failure disruption, potential for risk reduction, and reliability enhancement, to produce a measurable financial indicator, such as the percentage or absolute reduction in risk, relative to each dollar spent or invested.

PORTABLE AND STATIONARY ESS

Electricity serves as the backbone of modern life, powering businesses, cities, and homes. Without reliable battery systems, these sectors would struggle to operate efficiently and sustainably, leading to increased energy waste, higher costs, and environmental harm. Batteries, as both a source and storage medium, enable devices and technologies to function seamlessly on the move. Emerging portable energy storage solutions are poised to combat climate change, support the growth of renewable energy, decarbonize the economy, and reduce costs for consumers and businesses, fundamentally transforming technology and everyday life.

Energy storage plays a pivotal role in the power grid by balancing inputs from wind, solar, hydro, nuclear, and fossil fuel sources while enhancing demand-side management and overall system efficiency. By providing greater flexibility, storage facilitates the integration of renewable and distributed energy resources, increases the efficiency of existing infrastructure, and can reduce the need for new polluting peak power plants. It benefits consumers by lowering costs, improving reliability, and enhancing resilience, all while mitigating environmental impacts. Additionally, energy storage smooths out fluctuations in intermittent resources, like wind and solar, by capturing excess energy when production is high and releasing it when demand rises. This capability allows storage systems to inject or withdraw electricity as needed, ensuring a precise match between supply and demand at any time and location.

Portable Renewable Storage Systems

Portable renewable energy storage systems are self-contained units that harness renewable sources, such as solar or wind power, and operate independently of the main electrical grid. Unlike conventional portable gas generators, these systems do not require fuel, which reduces operational costs, weight, and storage requirements. They are particularly valuable during emergencies or disaster situations. Mobile solar or wind setups can be transported to remote or temporary locations where electricity is needed. These systems can be mounted on trailers or carts, making them easy to move and deploy to power field hospitals, shelters, campsites, kitchens, or other facilities requiring electricity.

Standalone renewable energy systems offer an economical alternative to fossil-fuel-based generators for homes or commercial sites in rural or hard-to-reach areas, where extending power lines from the main grid is costly or impractical. These units are suitable for long-term use, providing electricity for households, businesses, communication stations, agricultural equipment, and more. Despite their compact size, they can support critical devices such as medical equipment, computers, communication tools, and lighting. Additionally, solar and wind energy can be integrated into specialized standalone devices like water purification units. Energy storage allows these systems to capture and store power from intermittent sources, enabling electricity availability according to demand rather than weather conditions.

Recently, four key trends have been reshaping the power sector and fueling advancements in energy storage technologies.

- *Grid-level Decarbonization:* Renewable energy is projected to account for over 30% of global electricity by 2040. Integrating renewables allows electricity supply to be less dependent on variable weather conditions, helping grid operators maintain a stable balance between generation and consumption in real time.
- *Digitization:* The rise of connected devices, smart sensors, and the broader Internet of Things (IoT) empowers decision-makers with real-time data, enabling more informed and precise management of power systems.
- *Decentralization:* Consumers are increasingly becoming active participants in the energy system, contributing to a more distributed and flexible power network.
- *Electrification:* There is a growing shift toward electrifying various segments of the energy ecosystem, supporting cleaner and more efficient energy use across sectors.

Stationary ESS

A stationary energy storage system is designed to store electrical energy and supply it when required. Typically, such a system consists of a battery array, a control electronics unit, an inverter, and a thermal management system, all housed within a single enclosure, as shown in Table 2.

Table 2. ESS batteries according to various global standards.

Standards	Standard Details
IEC 62619	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Safety requirements for secondary lithium cells and batteries, for use in industrial applications.
IEC 62620	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Secondary lithium cells and batteries for use in industrial applications.
IEC 63056	Secondary cells and batteries contain alkaline or other non-acid electrolytes.
	Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems.
VDE-AR-E 2510-50	Stationary battery energy storage system with lithium batteries–Safety Requirements
UL 1973	Standard for safety–Batteries for use in Light Electric Rail (LER) applications and stationary applications.
JIS 8715-1	Secondary lithium cells and batteries for use in industrial applications–Part 1: Tests and requirements of performance.
JIS 8715-2	Secondary lithium cells and batteries for use in industrial applications–Part 2: Tests and requirements of safety.
UL 9540A	Evaluating thermal runaway fire propagation in battery energy storage systems.

Energy storage systems (ESS) are essential for addressing the variable output of renewable energy sources and ensuring a stable energy supply. In recent years, battery energy storage systems (BESS) have emerged as the most widely used technology, driven by declining costs and technological improvements. Nevertheless, ESS encompasses more than just batteries. While many alternative storage technologies are still in development and not yet commercially viable, evaluating their advancements and limitations remains important. Over the past decade, wind and solar power have become increasingly prominent in renewable energy generation, contributing a larger share to the energy mix. With the rapid growth of global solar photovoltaic (PV) installations and ongoing technological innovations, this article focuses primarily on energy storage systems applicable to solar energy, which can be broadly classified into three main categories,

- *Utility-Connected Systems:* Also known as grid-tied systems, these setups allow excess renewable energy to be fed back into the electrical grid. An inverter is used to convert the system's DC output into AC electricity that matches the phase and frequency of the local grid. When renewable energy generation falls short, the local utility compensates for the deficit.
- *Standalone Systems:* Commonly used in industrial and residential settings, such as traffic signals, remote power sites, and electric vehicles, standalone systems utilize the energy generated directly without sending surplus power back to the grid. Any excess energy is typically stored in batteries or other energy storage solutions for later use.
- *Hybrid Systems:* Considered the next step in energy management, hybrid systems combine renewable generation sources like solar and wind with storage solutions and, optionally, grid connectivity. This integration enhances overall efficiency and ensures a more stable and reliable energy supply.

Energy Storage System (ESS) Technology Types

The energy produced by solar sources is initially in the form of electricity, which can either be stored directly or transformed into another form before storage. Among the various energy storage solutions, some notable Energy Storage Systems (ESS) convert renewable energy into mechanical energy for storage. These systems include Pumped Hydro Storage (PHS), Flywheel Energy Storage (FESS), and Compressed Air Energy Storage (CAES). Mechanical energy storage functions by harnessing kinetic forces, for instance, by spinning a flywheel. While the underlying physics is straightforward, these storage systems rely on advanced materials and sophisticated computer control technologies to operate efficiently.

- *Pumped Hydro Storage (PHS):* This method stores energy by utilizing the potential energy of water. During periods of low electricity demand, excess electrical energy is used to pump water into an elevated reservoir. When electricity is needed, the stored water is released to generate power quickly. The volume of water and the height from which it falls determine the amount of energy that can be stored.

- *Flywheel Energy Storage (FESS):* FESS stores energy as the kinetic energy of a spinning rotor. The flywheel accelerates to store energy and decelerates to release it, with minimal frictional losses. The energy stored depends on the flywheel's rotational speed and moment of inertia. Electricity from renewable sources is used to spin the flywheel and recover energy as needed.
- *Compressed Air Energy Storage (CAES):* Similar in concept to PHS, CAES stores excess energy by compressing air or another gas into underground chambers. When electricity is required, the compressed air is heated and expanded through a turbine, driving a generator to produce power.

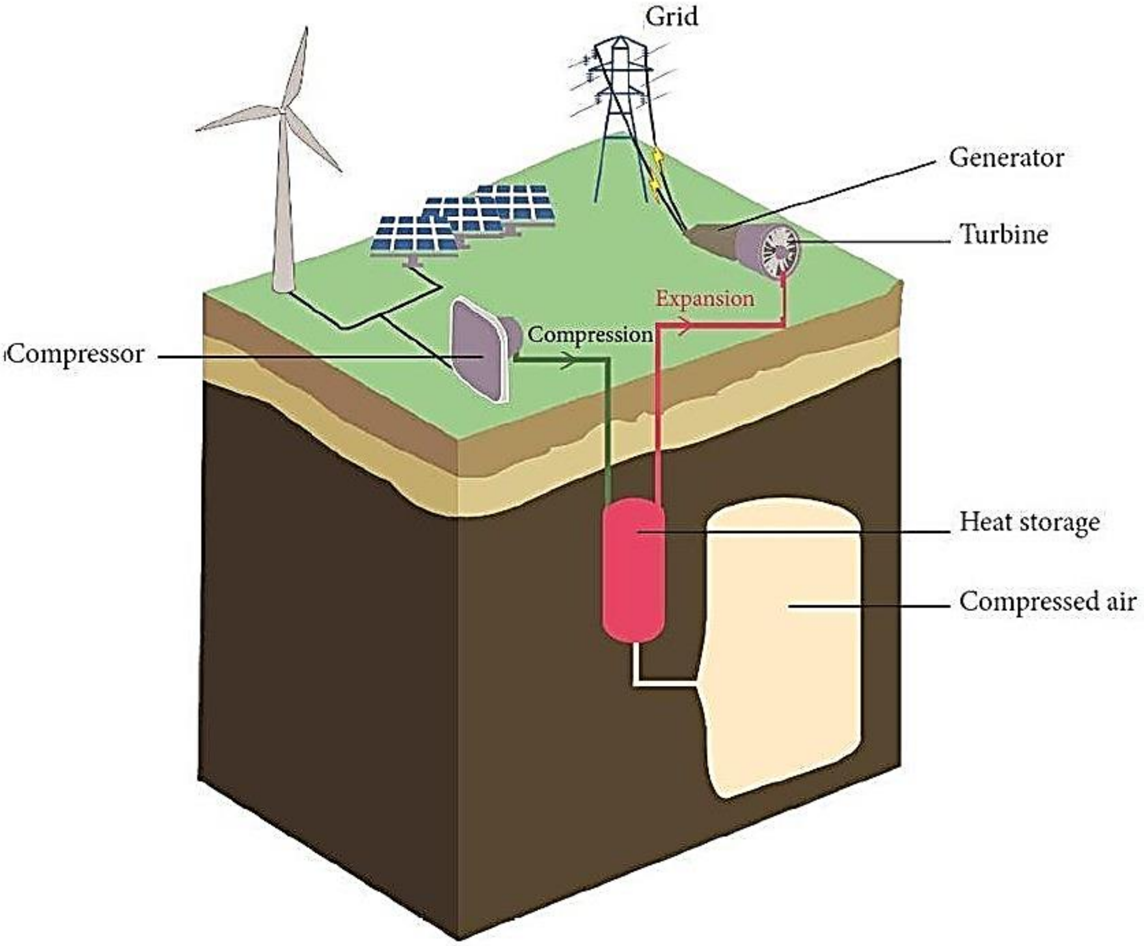


Figure 20. Energy storage system (ESS).

As the term implies, electrical storage systems (ESS), illustrated in Figure 20, store energy in electric rather than mechanical form, unlike the previously discussed methods. Examples of such systems include supercapacitor-based ESS and superconducting magnetic energy storage (SMES) systems. Supercapacitor ESS employ one or more supercapacitors, which are electrostatic capacitors with energy densities approximately 10 to 100 times greater than those of conventional electrolytic capacitors. This makes them ideal for applications requiring frequent charge and discharge cycles, although they are less suited for long-term energy storage. In contrast, SMES stores energy in a magnetic field, generated by passing direct current through a superconducting coil, often made of materials like mercury. SMES is generally used for short-term storage but is limited in widespread utility-scale adoption due to its high cost. Electrochemical storage, commonly referred to as Battery Energy Storage Systems (BESS), relies on rechargeable batteries. Current battery technologies include lead-acid, alkaline, silver-based, lithium–ion, sodium–sulfur, and flow batteries. Among these, lithium–ion batteries dominate the solar-plus-storage sector because of their affordability and availability, although alternatives, like flow batteries, have been increasingly developed and implemented.

CONCLUSIONS

The study of microgrid sources and power electronic interfaces demonstrates the growing importance of microgrids in the current power systems, particularly when considering the integration of renewables, energy security, and grid resilience. The ability to run in grid connected and island mode also makes microgrids flexible in the management of distributed energy resources and in boosting power reliability. The analysis of microgrids sources allows seeing the variety of the available generation types, such as solar photovoltaic (PV) systems or wind turbines, diesel generators, or combined heat and power units. The sources are characterized by various peculiarities, strengths, weaknesses, and require a careful choice to be made depending on the conditions of the chosen site, the load requirements, and economic factors. Although being environmentally friendly, renewable sources need strong interfacing and control mechanisms because they are intermittent in nature, and their output varies. Power electronic interfaces are very important in the process of bridging the gap between the sources in the microgrids and the loads or the main grid. The construction and operation of these interfaces of AC and DC sources are crucial towards effective energy conversion, regulation of voltages and stability of frequency. The study also highlights the significance of enhanced inverter structures, two-way converters, and hybrid AC/DC designs to optimize the use of energy and at the same time enjoy a chance of flexibility of operation. In addition, microgrids can be further increased in stability and reliability by the integration of energy storage systems (ESS), portable and stationary. ESS enables load leveling, peak shearing and compensation over renewable intermittency, hence maintaining power availability and enhanced power quality. Microgrid design is also in need of protection, coordination, and power quality management. This paper describes typical frustrations of the identification of faults, harmonics, voltage sags, and frequency deviations and explores some of the solutions, including sophisticated coordination of the relay, active filtering, and real-time monitoring methods. Not only should protection schemes and the quality of power be guaranteed so that the microgrid components are not threatened but also providing stable work when it must interact with the main grid. Overall, the study highlights the importance of effective implementation of microgrids, which depends on the integration of varied energy supply, advanced power electronic interfaces, and effective protection and energy storage systems. Microgrids may play a significant role in managing sustainable energy, improving resiliency, and decentralization of power networks by addressing technical, operational and economic factors. The knowledge gained in this study gives a broad base, upon which more research, optimization, and application of microgrid technologies can be done in different application settings.

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