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Review

A Review on Active-Power-Sharing Techniques for Microgrids

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Abstract: This paper provides a thorough examination of various techniques for sharing active power between multiple dispatchable generation sources distributed within an interconnected microgrid. Ideally, an interconnected microgrid should function as a consistent load or source. However, achieving this ideal operation requires compensating for natural load fluctuations and the intermittent power output from non-dispatchable energy sources within the microgrid through timely and adequate adjustments made by dispatchable generation. Numerous control and management systems have been documented in the existing literature to achieve optimal microgrid operation. This paper presents a concise comparison of most of the proposed systems published in the literature. The benefits and restrictions of the proposed methods are thoroughly evaluated under various possible operating scenarios.

Keywords: microgrids; power sharing; dispatchable and non-dispatchable generation; droop control

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1. Introduction

The concept of microgrids, which involve integrated renewable energy sources, has transformed from a mere concept to a tangible reality in today's world. With the rapid expansion of distributed power generation sources, microgrids have emerged as a practical and versatile solution for disintegrating huge grids into smaller and more manageable systems. This development has been driven by the increased energy efficiency of distributed conventional power generation sources and the widespread availability of renewable energy sources at domestic and commercial levels. These factors have played a key role in fostering the evolution of microgrids [1].

Microgrids are becoming an increasingly popular solution for managing power systems with a high percentage of renewable penetration. They offer a flexible and decentralised approach to energy management, allowing communities and organizations to participate in the energy market, store, and distribute their own electricity. This approach can increase energy efficiency, reduce costs, and improve the resilience of the overall power system [2].

In a microgrid, power generation sources can include both conventional and non-conventional (renewable) energy sources, such as wind, photovoltaic, energy storage (fly wheels or chemical storage batteries), which can store excess energy for later use. As such, advanced control systems are essential to manage the flow of electricity within the microgrid, optimise energy utilisation, and reduce losses [3].

The widespread adoption of microgrids has been driven by a number of factors, including the availability and cost-effectiveness of renewable energy sources, the desire to develop independent and resilient power systems, and the need to reduce carbon emissions and combat climate change. As technology continues to advance and the benefits of microgrids become more widely recognised, it is expected that a greater adoption of this energy management approach will dominate the energy market soon.

Conventional power generation follows a centralized model where electricity is produced in large quantities at a central facility, often located far away from consumers. The

generated power is then transmitted through transmission lines and is distributed through passive distribution networks. This long-standing model has successfully served the energy requirements of large populations over many decades.

However, this model has some drawbacks. For one, it is often expensive to build and maintain large power plants and transmission networks. In addition, substantial transmission losses can occur during long-distance transmission, reducing the efficiency of the system. There can also be reliability issues, such as power outages, that affect large areas.

The development of distributed power generation, such as microgrids, has the potential to address some of these drawbacks by bringing power generation closer to the point of use. By generating power locally, either through renewable sources or through smaller and more efficient conventional sources, it is possible to reduce transmission losses and enhance the efficiency of the overall system. It can also enhance the resilience of the system by minimising the impact of power outages of large areas.

Another challenge with the traditional centralised model is that it is vulnerable to disruptions, such as natural disasters or cyberattacks, which can cause widespread power outages. Microgrids of distributed energy resources are seen to improve the resilience and reliability of power systems by creating smaller, and more flexible networks that can operate independently [3–6].

Overall, while the traditional model of centralised power generation and distribution has performed well in the past, it is clear that new models and technologies have become essential to meet evolving modern needs.

Extensive AC interconnected power systems have been established globally, linking remote power generation sources to consumers. These grids consist of a network of high-voltage transmission lines, substations, and medium/low voltage networks that enable an efficient and reliable transfer of electric power over vast distances.

The development of AC interconnected power systems began in the early 20th century and was driven by the need to connect remote power generation sources, such as hydroelectric power plants, to urban centres and industrial areas. These systems have since expanded to cover vast geographical areas and are capable of delivering large amounts of electricity to millions of consumers.

One of the key advantages of interconnected power systems is the facilitation of efficient sharing of power resources across a wide area. This means that when one area experiences a shortage of power, electricity can be quickly and easily transmitted from another area with excess power. Interconnected power systems also facilitate the integration of diverse power generation sources, especially renewable sources such as wind, solar, and others.

Despite their advantages, interconnected power systems are also vulnerable to disruptions, such as severe weather events or cyberattacks, which can cause widespread power outages. As a result, there is an increasing interest in developing more localised, distributed power systems such as microgrids, which can operate independently in an islanded mode of operation and while connected to the main grid.

In Australia, a large, interconnected power network has been developed that is currently interconnecting five eastern and southern states and territories, namely, Victoria, Canberra, South Australia, Tasmania, Queensland, and New South Wales [7]. The network spreads over 5000 km from South Australia to Queensland and is operated as the National Electricity Market (NEM). Figure 1 shows the overall spread of this network which has around 200 large generators and 13 major distribution networks, delivering around 200 TWh of electricity annually.

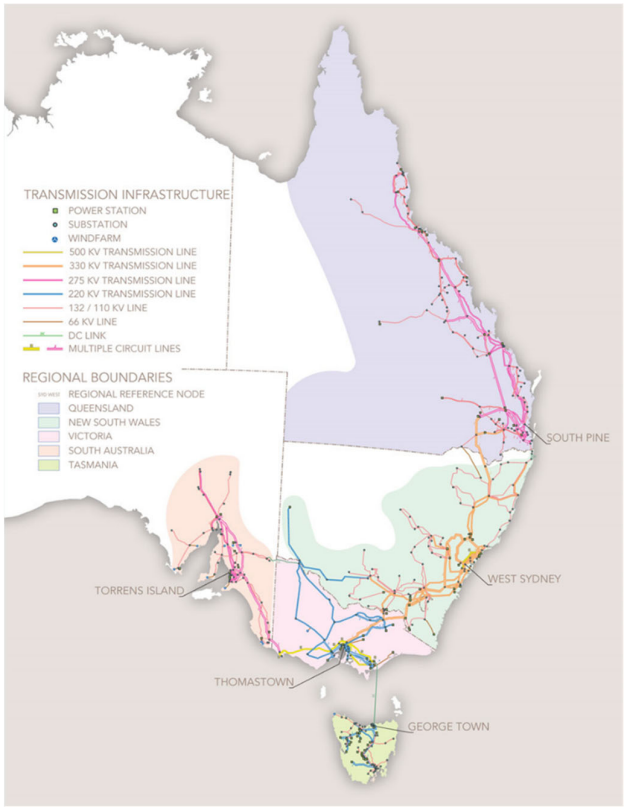


Figure 1. Australia's interconnected system [8] (source: AEMO through AEMC).

Traditionally, operating a specific segment of a network in isolation, even with an ample supply of distributed power generation sources, was not initially regarded as a favourable or recommended practice for many utilities [8]. It was only recommended for extraordinary operational circumstances as the overall control and protection systems were not specifically designed to support such operation. In the present days, microgrids are recognized as a smart, practical, and sustainable option for grid operators. This shift in perception is driven by the desire to fully leverage the advantages of higher levels of penetration of distributed power sources, the availability of efficient and cost-effective distributed generation technologies, and the need to reduce the expenses associated with maintaining a reliable and redundant grid infrastructure [8]. Owing to the obvious economic and environmental benefits, the model of having operational microgrids has been investigated in the literature in detail. Numerous studies are conducted and reported to evaluate the possibility of the independent, isolated operation of a microgrid under various operating conditions. The research conducted in this particular field has garnered significant interest and attention from researchers.

Australia, being at the forefront of grid evolution, is not only witnessing this transformation but embracing it to ensure their power systems also evolve according to the modern-day requirements of having an environmentally friendly green and sustainable energy infrastructure; an infrastructure that can facilitate higher levels of renewables penetration without compromising system reliability and security. Australia, while having a large, interconnected power network on the eastern coast, also has four operational microgrids on the western side (WA) to serve remote industries and communities [9,10]. The four microgrids in WA are: Perenjori, Bremer Bay, Kalbarri, and Ravensthorpe.

Figure 2 shows the four microgrids operating in the South-West Interconnected System (SWIS) in WA. The Ravensthorpe microgrid was formed almost a decade ago, while the other three were formed in the last 6 years; Bremer Bay in 2017, Perenjori in 2018 and Kalbarri in 2021.

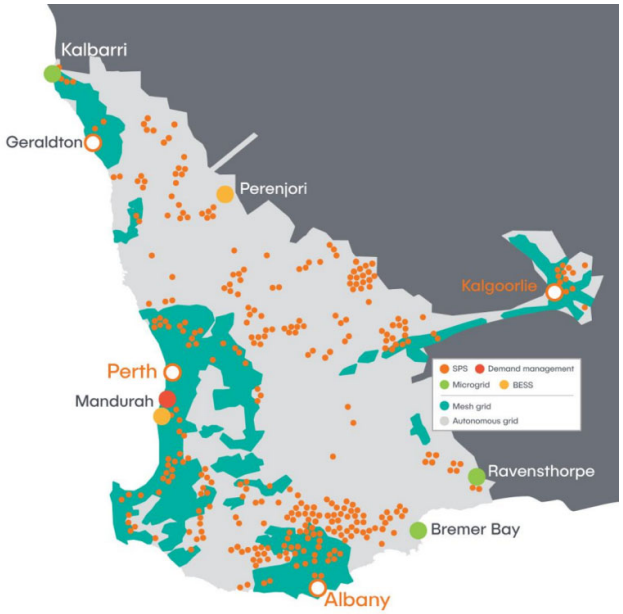


Figure 2. Microgrids and interconnected network map of WA [11].

Kalbarri being the largest microgrid in Australia (Figure 3) is operating only on renewable sources, comprising 1.6 MW of wind generation, 1 MW of roof top solar, and 2 MWh of battery storage. The microgrid in Kalbarri is a grid connected microgrid. The grid can provide additional demand especially during the tourist season; however, the microgrid itself can operate on its own in case grid interconnection is lost due to any network abnormal event [11].

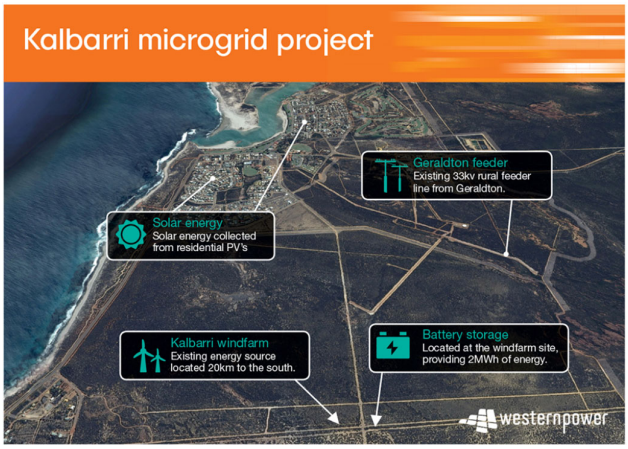


Figure 3. Geographic view of Kalbarri microgrid [10].

Apart from Western Power of Western Australia, several other power utilities throughout the world now also operate and maintain numerous microgrids. Studies related to the stable and efficient design and operation of microgrids have lately attracted a lot of interest in academia and industry [12]. The global market of microgrids is expected to grow to a value of US25.04 b in 2026 from just US9.63 b in 2022 at a 20.4% Compound Annual Growth Rate (CAGR) [13].

In the US, there are 160 microgrids in operation, mostly concentrated in seven states: Alaska, Georgia, California, Texas, Maryland, Oklahoma, and New York. These provide almost 0.2% of US electricity [14].

Microgrids having multiple grid connections to either a single grid or multiple grids are a unique case, which has yet to be thoroughly investigated in the literature. Multiple connections to one grid or multiple grids can be required for several operational reasons,

primarily reliability [15]. Several sensitive installations related to defence or process-critical industry might have additional reliability requirements. With recent advancements and the benefits of operating a dis-integrated power system, it is likely that state level systems operating as large microgrids will be seen in the near future. If this hypothetical scenario is applied to the Australian network, it is possible that all or one interconnected state(s) will be operated as large microgrids. If we consider Queensland (QLD), at the north end of the interconnected NEM network, is being operated as a large microgrid then it has already multiple interconnections with New South Wales (NSW). This can be regarded as an example of a future microgrid with multiple interconnections. The two interconnections are not only at different nodes but are also quite different, as one is an AC interconnection while the other is a DC link. The DC link is called a Direct link, which is a 110 kV DC link with flow limits given in Table 1 [16].

Table 1. Direct link active power flow limits.

From	To	Nominal Capacity
NSW	QLD	107 MW
QLD	NSW	210 MW

The other interconnector is called the QNI—Queensland to New South Wales interconnector. This interconnector consists of:

- A 330 kV double-circuit transmission line connecting Armidale, Dumaresq, Bulli Creek, and Braemar substations;
- 375 kV dual-circuit transmission line connecting Braemar and Tarong substations;
- Two transformers of 330/275 kV at Braemar substation.

The overall active power flow limit on the QNI is given in Table 2. These overall flow limits in the existing interconnection, with several lines, demonstrate that a flow control based on the sum of active power flows on multiple lines is a real example.

Table 2. QNI active power flow limits.

From	To	Nominal Capacity
NSW	QLD	300–600 MW
QLD	NSW	1078 MW

Several technical and commercial challenges related to microgrid operations have been noted and several resolutions are proposed [17,18]. A key technical concern regarding the optimal functioning of a microgrid revolves around the efficient distribution of active power among its dispatchable distributed generation units (DDGUs). In the case of a microgrid consisting of a single large dispatchable generation unit, such as a synchronous machine or a dispatchable energy storage system, alongside other smaller non-dispatchable distributed generation units (NDDGUs), primarily renewable energy sources of intermittent characteristics, the sole dispatchable unit is responsible to compensate for any fluctuations in the generation or demand. If a microgrid incorporates multiple dispatchable generation units, they must be fully coordinated to effectively respond to changes in load demand, active power generation, and changes in network configuration.

Changes in network configurations, load distribution or load concentration either caused by the emergence of a new load centre or a generation station within a microgrid can result in a completely different active power flow within the microgrid. In evolving modern-day power systems, such changes are highly probable. In a case where the performance of active power sharing control within a microgrid is dependent on the network configuration, then for any and every modification in the network, the whole algorithm of active power sharing will have to be revisited or retuned according to the new operating conditions.

Mostly, this aspect of the performance criterion is found to be missing for the methods which are presented in the literature so far [1,19].

MicroGrids

According to the IEEE "A micro grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid." [20].

Microgrids are roughly classed into two types, based on their connections to the main grid: interconnected microgrids and isolated microgrids [21]. Isolated microgrids, as the name suggests, have no linkage with a larger grid or a power system, but interconnected microgrids can have one or multiple links to one or more grids or power systems. An interconnected microgrid, on the other hand, may or may not remain connected to the other grid(s). It may operate in three different modes:

1. Linked to the main grid(s) (Grid Connected Mode);
2. Isolated;
3. Transition [22–24].

The detachment from the main power grid might be either intentional or unintentional. In any operational scenario, the microgrid must be able to maintain its stability while in any mode of operation at any given moment [25]. Types of microgrids are summarised in Figure 4.

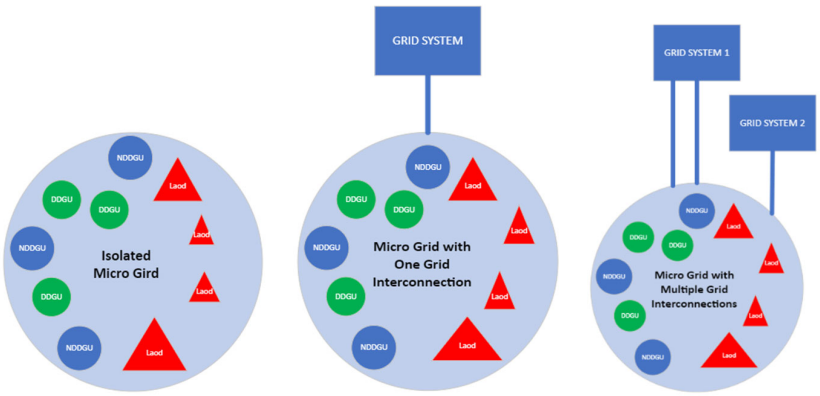


Figure 4. Types of microgrids.

Apart from the basis of grid interconnection, microgrids can also be classified based on the category of load they serve, for example, residential, commercial, or industrial.

The fundamental operational difference between a microgrid with a single grid interconnection and one with multiple grid interconnections is the way in which interconnection flows are managed or controlled. A microgrid with multiple interconnections from one grid system at the same voltage level and at the same interconnecting node is operating almost like a microgrid with one connection to the grid, apart from having increased reliability. However, a microgrid with multiple connections to a single grid system but at different connecting nodes or at different voltage levels is quite different in terms of controlling or managing the flow of active power to or from the connected grid system. Controlling active power flow over the interconnector lines is significantly more challenging in such networks.

Microgrids which are connected to a grid should ideally function as a constant load or a constant power source for the main grid while interconnected [26]. A microgrid can only achieve this ideal operational scenario if the DDGUs within the microgrid can compensate for the fluctuations in its local load or generation. DDGUs need to react positively to any variations in load or generation, which can be caused by the intermittency of renewable energy sources or due to a failure of any power-generating facility [26–28]. The task of achieving optimal operation in microgrids with higher levels of renewable energy

integration and fluctuating demands presents greater challenges compared to microgrids with lower renewable energy penetration and stable load characteristics.

The progress made in inverter-based renewable generation (IBRG) technologies has enabled the conversion of NDDGUs into partially dispatchable power or energy sources by the integration of battery energy storage systems (BESS). Additionally, advancements in power electronics-based technology have led to the development of grid-forming inverters, which can offer cutting-edge grid supports including virtual inertia, and very fast frequency response. These innovations helped the concept of the independent operation of microgrids relying entirely on IBRGs to meet their energy requirements [29,30].

The primary challenges faced by current microgrids can be outlined in the bullet points below:

- Achieving optimal operation of an interconnected microgrid, as a constant load or a steady source for the main grid;
- Coordinating the microgrid's response to internal variations in generation or demand;
- Warranting stable and reliable performance for any mode of operation;
- Maintaining specific levels of active power flowing through interconnection links.

Apart from the challenges listed above, microgrids face other challenges that must also be addressed in order to ensure their successful implementation and operation. Addressing these challenges will require a coordinated effort from stakeholders including industry, government, and academic institutions. With the right investments in technology, policy, and infrastructure, microgrids have the potential to revolutionise the way electrical energy is generated, distributed, and consumed. Some of the secondary challenges of microgrids include:

- Cybersecurity: Microgrids are vulnerable to cyberattacks, which can disrupt their operation and potentially cause damage to equipment. This requires robust cybersecurity measures to protect against threats such as hacking and malware.
- Finance and Economics: Microgrids can be expensive to implement, particularly in remote or rural areas. The economics of microgrids must be carefully considered to ensure they are financially sustainable over a long term.
- Regulatory and Policy Frameworks: Microgrids may face regulatory and policy barriers that make it difficult to implement in certain regions. Clear and supportive regulatory and policy frameworks are needed to encourage the development of microgrids and ensure their integration within larger power grids.
- Technical Standards and Interoperability: Microgrids rely on a variety of equipment and technologies, and ensuring they are interoperable and compliant with technical standards is critical to their successful operation.

2. Power-Sharing Techniques

Numerous approaches have been proposed to facilitate efficient distribution of active power among DDGUs in microgrids. One commonly employed approach is the utilization of a power-frequency (P-f) droop control, which has been extensively adopted in different ways to achieve appropriate power sharing among the DDGUs [22].

Traditionally, these droop controllers have proven to be a time tested, reliable, robust, and simple method for controlling the active power output of DDGUs in response to a changing load within a microgrid. Numerous studies have utilized P-f droop control for ensuring that the system effectively meets the fluctuating demand through dynamic unit response [23]. By utilizing a uniform frequency signal across all generating units, it can easily adapt to the required variations without requiring additional signals. The droop constant value is pre-set and remains fixed for each unit in conventional approaches. However, alternative techniques suggest that the droop constant should be periodically adjusted based on the unit's operating conditions and the overall system [25–27]. These controls are classified as adjustable droop-type controls, while the traditional approaches are regarded as constant or fixed droop controls.

Instead of basing droop settings on the capacity of DDGUs, a droop controller is proposed in [26] in which the droop settings are continuously adjusted based on the current reserve of the DDGUs. In the traditional approach, DDGU operators typically do not favor adjustable droop controllers as this may result in sporadic changes to the active power output of the unit at different rates. This can lead to increased mechanical wear and tear on various hardware components such as valves and pumps.

Constant droop-based methods have demonstrated their suitability and robustness in microgrid applications. However, if the value of the droop constant depends on the network configuration and/or the number of generation units in the system at a given time, the method can be considered a hybrid between adjustable and constant droop systems. In such scenarios, if a central controller is unavailable for a certain time, then operators would need to manually calculate the new droop constants for each unit.

A microgrid that is tightly connected to a larger and more powerful grid may not encounter frequency changes due to internal load or generation fluctuations. In this scenario, the frequency of the microgrid can be controlled by the larger grid, maintaining a constant value. This can pose a challenge to the effectiveness of the P-f droop mechanism, as the microgrid's frequency is dictated by the external grid.

A method presented in [6] has focused on the economic dispatch of the generators by separating the microgrid into smaller areas. In [29], a proposal is made for a centralized power-sharing mechanism that utilizes a web-based communication system with low bandwidth.

In [31], a research study introduced two adaptive and intelligent control techniques designed to manage the voltage and frequency of a microgrid in both islanded and grid-connected modes, facilitating a seamless transition between the two operational modes. The proposed controllers utilize H-infinity along with model predictive control methods to enhance the performance of the P-f droop control algorithm. The H-infinity control approach is employed to control the microgrid during islanded operation and ensure a smooth transition between the microgrid's operational modes.

Based on the same harmony search-based H-infinity control, an addition to droop control is provided for tighter regulation of the microgrid's frequency and voltage [32]. The proposed control strategy improved power quality performance in an isolated microgrid. A control approach is recommended for contemporary inverters with sophisticated characteristics such as virtual inertia or that may operate in a mode known as virtual synchronous machine (VSM) mode [33]. The harmony search-based H-infinity control algorithm has a disadvantage in final rounds where the pitch adjustable rate (PAR) value is close to zero, which may result in algorithm convergence performance stagnation.

Based on a fuzzy control with model predictive control (MPC), another suggested technique altered the inertia constant H and damping coefficient D of the swing equation given below.

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \tag{1}$$

$$M = \frac{GH}{\pi f} \tag{2}$$

$$\frac{2GH}{\omega}\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \tag{3}$$

In the above equations:

M = Angular Momentum;
D = Damping Coefficient;
H = Inertia Constant;
G = MVA Capacity;
ω = Angular velocity;
P_m = Mechanical Power;

P_e = Electrical Power.

This technique was shown to give improved frequency response for substantial load changes inside an islanded microgrid. A more hierarchical and further-refined control scheme with three levels of control is provided for tighter voltage and frequency regulation and optimisation inside an isolated microgrid [24].

A frequency and voltage controller based on distributed consensus is presented for improved frequency and voltage responsiveness during failures within an isolated microgrid [34]. This technique is presented only for islanded or grid-isolated microgrids. One disadvantage of fuzzy logic control systems is that they are entirely dependent on human knowledge. The rules of a fuzzy logic control system must be updated on a regular basis. Several MPC models can only handle steady, open-loop processes. To explain a response, MPC frequently requires several model coefficients. Some MPC models are designed for output disturbances and may struggle with input disturbances. Even if the model is correct, control performance will be poor if the prediction horizon is incorrectly stated [34].

Solar (PV) and wind power generation have traditionally been non-dispatchable, with regular operation relying on Maximum Power Point Tracking (MPPT) management. As a result, these can cause significant disruption to system dispatch, particularly in the context of microgrids. A unique power-sharing control (PSC) strategy is presented in [35] to manage wind and solar PV power production in microgrids to decrease the loss of energy production from renewable sources involved and to efficiently satisfy dispatch command or market schedules. While considering the various attributes of wind and solar PV power generating systems, the disparity between dispatch command (market timetable) and real renewable generation is initially offset by regulating wind power output by temperately storing or releasing kinetic energy of turbine rotors. This method does not look at overall active-power-sharing between all dispatchable generating units. Additionally, cascade control has three drawbacks. For one thing, it requires an extra measurement (typically flow rate) to function. Two, an extra controller must be calibrated. Third, the control technique is more difficult—for both engineers and operators [36].

The integration of renewable energy sources into off-grid systems is hindered by the inherent unpredictability of renewable power output. However, advanced control techniques offer the potential for more efficient utilization of non-dispatchable sources. In [37], a two-layer predictive management technique is proposed for an off-grid hybrid microgrid consisting of controllable and non-controllable generating units, as well as a storage system. The upper layer focuses on unit commitment, while the second layer governs real-time operations. A response filter is utilized to mitigate load volatility and ensure smoother operation of the microgrid.

Virtual synchronous generator (VSG) control for inverter microgrids have attracted the interest of researchers to solve the issues related to low inertia in microgrids with high renewable penetration. When there are uneven transmission line impedances, VSG management cannot assure proportional reactive-power-sharing across DG units, while active-power-sharing stays proportional among DGs [38]. An adaptive virtual impedance-based VSG control strategy for grid-connected and islanded microgrids is suggested in [21] to reduce impedance difference at inverter terminals and increase proportional reactive-power-sharing across DGs. The virtual impedance is made up of an adaptive virtual resistance and a fixed virtual inductance, with the virtual resistance being constructed adaptively depending on the microgrid's operation points.

As increasingly frequent and severe weather events interrupt the electricity system, there is rising concern about future grids' capacity to recover from such natural disasters. Microgrids have also been considered as a possible source of resilience. While most previous studies have focused on how to profit from existing microgrids through operating schemes, Ref. [39] focuses on microgrid planning to reinforce the network against major breakdowns. Three possible techniques are provided in this respect, with the goal of determining the ideal nodes for connecting microgrids as well as the capacity of the dispatchable generating units placed within microgrids.

A distributed technique is proposed in [40] for resolving a combined active and reactive power dispatch problem in only isolated microgrids. The information exchanged by surrounding local controllers enables the algorithm to achieve optimal dispatch in a secondary layer that serves as a reference for main controllers in each generator. The population dynamics-based strategy simplifies deployment in systems with high penetration of dispersed generation and a rudimentary communication network. The hierarchical method is tested in a co-simulation platform to simulate real-world situations in a case study of a microgrid with a management control scheme developed using the distributed optimisation technique.

In [41], a method is introduced for frequency management and active-power-sharing in an islanded microgrid by employing a communication mechanism which is event-triggered. The proposed approach combines active-power-sharing and frequency regulation within a unified framework through a distributed secondary control scheme. This scheme incorporates a sampled-data-based event-triggered communication mechanism, allowing neighborhood sampled-data exchange only when a predefined triggering condition is violated. When compared to standard periodic communication methods, the suggested event-triggered communication mechanism outperforms them in terms of minimising the number of communications between neighbours while maintaining the required performance level of microgrids. The Lyapunov-Kravovskii functional technique is used to construct certain necessary criteria for characterising the impacts of control gains, system characteristics, and sampling time on microgrid stability.

The Industrial Internet of Things (IIoT) is an architecture that leverages the Internet of Things (IoT) and cloud computing to enable distributed control of current industrial systems such as AC smart microgrids [42]. The research in [43] presented a unique safe energy policy and load sharing strategy for renewable microgrids for off-grid independent usage with power electronic jointing (PEJ) established in the IIoT context. It is assumed that an upper layer performs system dispatch computations, while a lower layer calculates correct control procedures for the PEJ. Based on communication, a decentralised multi-agent system (MAS) implements the upper layer of intelligent control. The high investment cost is one of the obstacles and cons of using IIoT for microgrid operations, and the high cost of adoption is one of the most visible industrial IoT concerns. It is imperative that data storage and management are secure; IoT devices create a TON of data and experience frequent connectivity outages [44]. Because generating units are naturally scattered, distributed control mechanisms are extensively used for AC autonomous microgrids. However, because a supplemental communication network is still required for transmitting information among surrounding generators, active power deviations may be harmed by various communication interruptions.

Achieving precise power sharing in islanded microgrids is a challenging task due to various factors, including impedance mismatches in the feeders. To tackle this issue, Ref. [45] proposes an event-triggered and distributed power-sharing method. The suggested approach dynamically manages virtual impedances at fundamental positive/negative sequence and harmonic frequencies, enabling distributed generating units to effectively exchange reactive, unbalanced, and harmonic powers. The proposed solution does not require knowledge of the feeder impedance and utilizes information transmission among units only during event-triggered periods, reducing communication overhead while maintaining system performance.

Ref. [46] provides a dispatchable droop control mechanism for multiple distributed generators that may be used in isolated AC microgrids. The suggested solution employs first-order inertia components to create pseudo-hierarchical control, allowing the generators to automatically divide the load on a smaller time scale while obeying the dispatch order on a larger time scale. The suggested technique incorporates both active power regulation and frequency restoration control. For different scenarios, it has either the reactive power regulation control or the voltage control. Even when the stated power control references

are infeasible, the proposed approach remains relevant. The efficiency of the suggested strategy is demonstrated via a MATLAB/Simulink simulation.

In reference [47], the paper focuses on addressing power-sharing and power quality enhancement issues in single-/three-phase islanded microgrids (S/T-MGs) that involve unbalanced sources and loads. To tackle these challenges, a hierarchical distributed control approach is proposed. This approach comprises three main components:

1. A phase-independent virtual synchronous generator (P-VSG) control, which serves as the primary control for distributed generators;
2. A distributed secondary power flow regulator, responsible for power-sharing control among distributed generators and balancing power flow between different phases;
3. A distributed secondary voltage regulator, dedicated to voltage restoration and improving power quality in the microgrid.

In [48], the paper introduces two distinct approaches by utilizing two modes of dispatchable distributed generation unit (DDGU) operation, named the unit power control (UPC) mode and feeder flow control (FFC) mode. The same was also suggested in [23,49]. A particular issue was spotted in [48] when several DDGUs operating in FFC mode are interconnected on the same feeder.

In [50], an alternative approach is proposed to tackle the challenge of real power-sharing among the dispatchable distributed generation units (DDGUs) in a microgrid. The suggested method emphasizes the importance of positioning the largest DDGU near the point of common coupling (PCC) or grid interconnection. This DDGU initially operates in feeder flow control (FFC) mode, while the remaining DDGUs operate in unit power control (UPC) mode. As the load increases and the FFC unit becomes fully loaded, the next DDGU in the queue switches to FFC mode. This sequential process continues, with DDGUs transitioning to FFC mode once the preceding DDGU reaches its maximum real power output.

Considering that the primary objective of power-sharing methods is to ensure the microgrid operates as a consistent power-consuming or power-supplying entity, it becomes necessary to operate one or more dispatchable distributed generation units (DDGUs) in feeder flow control (FFC) mode. To maintain sufficient reserve capacity in the DDGUs operating in FFC mode and compensate for any load or generation variations within the microgrid, it is preferable to maintain a high flow from the grid. However, it should be noted that if the flow from or to the grid is excessively high, it can result in larger frequency deviations during isolation or transition modes. Therefore, it is crucial to strike a careful balance to sustain unplanned isolation events in the microgrid.

The approach presented in [51] assumes the presence of a single dispatchable distributed generation unit (DDGU) at the beginning of each internal feeder in a microgrid. This arrangement allows for a constant power flow on each feeder by operating the respective DDGU in feeder flow control (FFC) mode. Maintaining a consistent flow on each internal feeder ensures an overall constant flow to or from the microgrid. However, this assumption of having a DDGU at the start of every internal feeder is both idealistic and restrictive. It is idealistic because the inclusion of numerous DDGUs within a microgrid can be considered an expensive luxury. Additionally, it is restrictive because the DDGU is limited to compensating for variations within its own feeder, even though it may have the capacity to contribute to variations in other feeders within the microgrid.

FFC and UPC control modes are referenced in several research papers, therefore some specific details are included in the following sections.

2.1. Power Control Modes

This section provides an explanation of two distinct modes of operation for Distributed Dispersed Generation Units (DDGUs), namely UPC (unit power control) and FFC (feeder flow control).

2.1.1. Unit Power Control (UPC) Mode

During the period when the microgrid is interconnected with the main grid, DDGUs operating in UPC mode ensure that a consistent output power level is maintained, irrespective of any fluctuations in load or generation. The frequency of the microgrid system is regulated by the main grid, and if all units within the microgrid operate in unit power control (UPC) mode, any variations in load can be compensated for by the main grid.

While a microgrid is isolated, the generating units operating in unit power control (UPC) mode will respond to the fluctuations in demand. A traditional power versus frequency (P-f) droop controller is employed, and the power is distributed among the units based on a constant droop controller parameter, K^U. The term "P-f" refers to the relationship between the real power output (P) and the frequency (f) of the microgrid. The droop parameter is used to regulate the rate at which the generator adjusts its power output in response to changes in the grid frequency.

P-f droop is commonly used in decentralised power systems with multiple generators, such as microgrids or islanded power systems. By using P-f droop control, the generators in the system can share the load and maintain stable grid frequency without the need for centralized control.

Overall, P-f droop is a simple and effective way to control the power output of generators in a grid and maintain stable grid frequency. It is widely used in decentralized power systems and is a key component of many modern power system control strategies.

The mathematical representation of the P-f droop controller is:

$$f' = f^0 - K^U(P' - P^0) \quad (4)$$

The variables K^U, f^0, P^0, f', and P' represent the UPC droop constant, initial frequency value, initial power value, final frequency value, and final power value, respectively. Figure 5 below shows the conventional P-f droop curve.

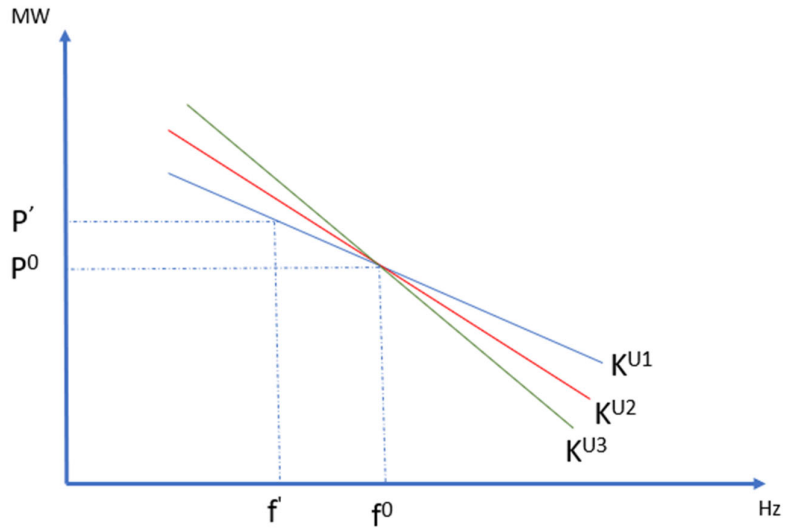


Figure 5. P-f droop curve for UPC mode of operation.

The units operating in the unit power control (UPC) mode can have either the same or different values of the droop parameter (K^U), which determines their respective influence on the changes in the operating conditions. The value of P_{ref}, which represents the preferred power level, is also dependent on the rating of each individual unit. Figure 6 depicts the operation of a unit in UPC mode in a microgrid. Once the microgrid is isolated, any load variation will result in change in the system frequency. The magnitude of the change in the frequency depends on the overall system-wide effective value of K^U.

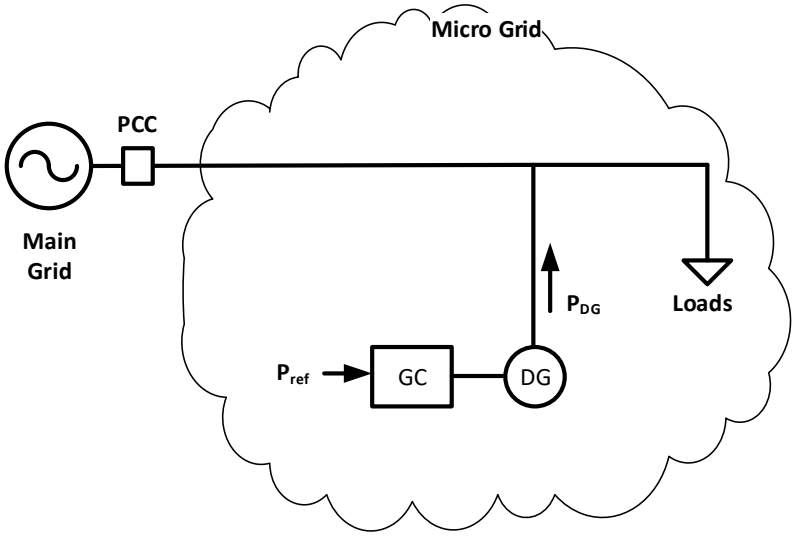


Figure 6. UPC mode of operation.

2.1.2. Feeder Flow Control (FFC) Mode

While a microgrid is interconnected with the main grid, the units operating in feeder flow control (FFC) mode are responsible for regulating the power flow at a specific location within the microgrid to a desired value referred to as FL_{REF}. For the units which are connected within the same internal feeder and operating in FFC mode, FL_{REF} is set to a value of FL_{FEEDER} ($FL_{REF\,1}$ = $FL_{FEEDER\,1}$ and $FL_{REF\,2}$ = $FL_{FEEDER\,2}$). In the event of an increase in load demand or a decrease in generation within the microgrid, the generation units operating in feeder flow control (FFC) mode adjust their real power output to ensure that the power flow at a specified location in the microgrid, known as FL_{REF}, is maintained at its designated value.

When a microgrid is isolated from the main grid, a feeder flow versus frequency (FL—f) droop controller is employed to sustain the active power flow at the designated location.

FFC mode can be represented mathematically as:

$$f' = f^0 - K^F \left(FL' - FL^0\right) \quad (5)$$

Variable K^F is the droop constant for FFC mode, while f^0, FL^0, f', and FL' are the initial and final values of frequency and power flow.

Figure 7 depicts the FFC mode of operation of a microgrid.

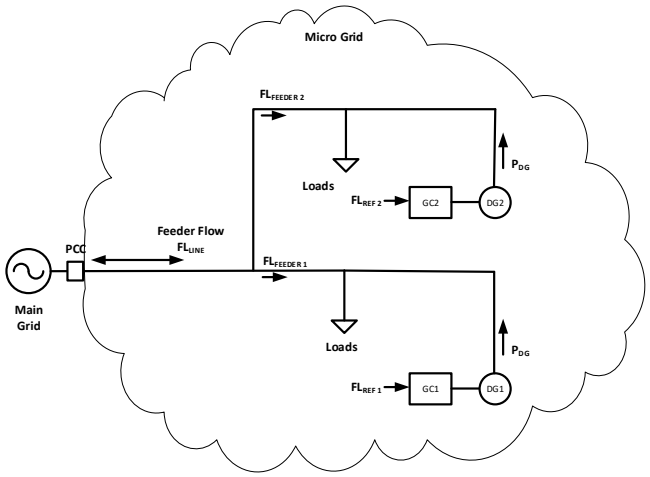


Figure 7. FFC mode of operation.

A comparison of the two recommended modes of operation is provided in Table 3.

Table 3. Comparison of UPC and FFC control modes.

Feature	UPC	FFC
Compensate internal generation and demand variations while connected to grid	No	Limited to connected feeder level
Ensure ideal operation of the microgrid in grid-connected mode	No	Needs as many DDGUs as the number of internal feeders
Compensate for the loss of DDGU within the interconnected microgrid	No	No
Respond to changes in the system frequency	Yes	Yes
Dependence on network configuration	No	Yes

2.2. Optimization

Optimization of the above-mentioned and other suggested active power-sharing techniques is a completely different topic altogether and is not intended to be discussed in detail in this article. However, some optimization methods which are proposed in the research to enhance the technical or financial efficiency of such active power-sharing methods are presented in this section.

To optimize the economic dispatch method for the power systems with the intermittent renewable NDDGUs, a sophisticated optimization technique is proposed in [52] based on a surrogate model. This model is based on a data-driven sparse polynomial chaos expansion, which enables accurate estimations of statistical information.

With high penetration of large-scale NNDGUs in a power system, optimization of the economic dispatch algorithm and to improve the stability of the overall system, [53] suggests integrating the small, distributed generation units and operate them as a Virtual Power Plant (VPP). A deep reinforcement learning (DRL) method is proposed which ensures optimal economic dispatch of the VPPs.

An advanced concept of an energy market, Energy Internet (EI) which has enhanced requirements operating efficiency for the generating units, has been proposed in the literature. In [54], a new feature of multi-energy coupling is proposed to enhance energy utilization. Since the suggested method is not restricted to only exchange of electrical energy, it is termed an indirect multi-energy transaction (IMET).

3. Conclusions

The active-power-sharing control mechanisms described above are primarily intended for microgrids with one active grid link or for isolated microgrid operation. The development of appropriate power-sharing strategies for microgrids with multiple active grid interconnections has received little or no attention. The suggested techniques have several limitations and are found to be effective for only one or a handful of operating conditions.

A wide variety of proposed active-power-sharing methods are based on droop control, which has several drawbacks that limit their applicability for a modern power system, and especially for a grid-connected microgrid or during the grid-connected mode of microgrid operation. Various issues have been reported in texts related to such systems, including poor transient performance, ignoring of load dynamics, and inability to impose a fixed system frequency. However, P-f droop-based active-power-sharing methods are found to be well suited for the island mode of microgrid operations.

Approaches that rely on a central master controller for load sharing among distributed generation units impose higher demands on the reliability of the communication and control infrastructure. Therefore, utilities and microgrid operators need to carefully choose the power-sharing method that aligns with the unique design and composition of their microgrid.

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