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Review

State-of-the-Art Literature Review of Power Flow Control Methods for Low-Voltage AC and AC-DC Microgrids

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Abstract: The development of AC distribution systems provides for the seamless integration of low-voltage microgrids with distributed energy resources (DERs). This poses new challenges for the control of normal, emergency, and post-emergency states of microgrids, calling for the creation and development of information and communications technology infrastructure. Power converters/inverters that are used to integrate renewable DERs lack inertia. Along with them, fossil fuel-fired generation units are also being integrated into microgrids. These include gas generator sets, diesel generator sets, and microturbines, having small (up to 1–2 s) values of mechanical inertia constants—*Tj*. This leads to an increase in the rate of transients by a factor of 5–10. Under these conditions, the technical requirements for the speed of automatic power flow control systems, as well as the methods they rely on, have to be reconsidered. Microgrids include DC microgrids, AC microgrids, and hybrid (AC-DC) microgrids. In the case of hybrid microgrids, DERs are connected to the DC grid and are integrated into the AC grid through a common inverter. The complexity of the task of microgrid control is due to the need to choose properly the type and extent of control actions so as to prevent the emergence and development of accidents. The employed control methods must ensure the reliable power supply to consumers and the quality of power in microgrids, as well as the reliable operation of the external distribution systems into which they are integrated. The article gives an overview of control methods for low-voltage AC and AC-DC microgrids, which allow one to tackle effectively solve the tasks.

Keywords: microgrid; distributed energy resources; generating set; renewable energy sources; inverter; converter; power flow control; control action

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1. Introduction

Decentralization of generation in the power systems of many countries around the globe is one of the trends of their development, that makes them live up to the environmental, socio-economic, and ethical expectations on the part of society [1]. Sustainable energy development is possible through the creation of modern technologies in the field of distributed energy resources (DERs).

DERs [2] include generation units based on renewable energy sources (RES): photovoltaic modules, wind turbines, etc. DERs also include fossil fuel-fired generation units—gas generator sets (GGS), diesel generator sets (DGS), microturbines, as well as energy storage systems (ESS) of various types, and fuel cells (FC) [3].

Integration of different DERs into distribution systems makes it possible to form small power systems, i.e., microgrids [4]. This allows mitigating the issues resulting from the separate use of DERs, including renewable DERs whose power generation is intermittent in nature, ESSs and fuel cells with high capital costs, as well as GGSs, DGSs, and microturbines with high maintenance and repair costs [5].

Reliability of power supply to consumers, power quality, and economic feasibility in microgrids is ensured by the implementation of control algorithms that take into account the features specific to different types of DERs. One of the features is the lack of inertia in renewable DERs as well as ESS and fuel cells [6,7] due to their integration into microgrids through power converters/inverters with almost zero inertia. Moreover, GGSs, DGSs, and microturbines have low values (1–2 s) of mechanical inertia constants—Tj, which leads to an increase in the rate of transients by 5–10 times [8]. Flexibility in microgrids is provided by the implementation of various control algorithms adapted to both grid-connected mode (operating in parallel to the external distribution grid) and islanded mode [9,10]. Switching of microgrids from one mode to another must take place without disturbing the operation of DERs and consumers. This is possible with the bumpless switching implemented by the static switch [11]. This requires a revision of the technical requirements for the speed of load-dispatching devices and the methods they use [12].

Microgrids can be built only on the basis of DC, AC, and AC-DC distribution systems [13]. The variety of types and configurations of networks requires the development of new principles for designing automatic control systems (ACS) and power flow control methods [14]. DC microgrids require a new grid infrastructure to supplement the AC grids in operation, which is costly. The article studies the principles of design of ACSs for AC and AC-DC microgrids. In the latter case, the DERs are combined over a DC grid, but are integrated into the AC grid through a common inverter [15].

Microgrids come in many different network topologies, such as radial, ring-shaped, and mesh structures, each with its advantages and disadvantages [16]. The most widespread is the radial network topology, on the basis of which open-ring circuits are implemented [17]. The mesh topology requires the construction of additional transmission lines, with which multiple network configurations can be implemented in microgrids. However, this contributes to the greater complexity of the ACS of microgrids, as it leads to changes in fault current levels, bi-directional power flows, load re-allocation between DERs, etc. [18].

Available review articles on the subject focused on its different facets, for example, the analysis of engineering solutions and methods of microgrid power flow control with their key advantages and downsides examined. Ref. [19] discussed the control principles of microgrids with different DERs. The study covered their mathematical models and recommendations for application in DC, AC, and AC-DC microgrids. However, the article failed to address the technical limitations of the considered control methods in existing distribution grids. Ref. [20] analyzed the structures of centralized, decentralized, distributed, and hierarchical control systems for microgrids, with examples of implementation of the most common control methods. That being said, the article lacked an analysis of microgrid structures and technical limitations on the application of the considered control methods. Ref. [21] examined the structures of microgrids, taking into account different aspects of their operation, and providing recommended practices for the implementation of various control methods. Ref. [22] presented a classification of the methods of primary control applied to microgrids. The classification was based on the (un)availability of communication links, with the advantages and downsides of each method identified. However, the implementation of the reviewed microgrid control methods was considered only in the case of AC grids. Ref. [23] addressed the issue of implementing a coordinated approach to the control of DERs, including ESSs, in the AC grid. The study also listed the technical requirements to be met by DERs to be able to control their voltage when operating as part of microgrids. In addition, Ref. [23] presented a comparative analysis of various control and optimization algorithms in microgrids, based on which control methods are adapted. However, the scope of the study was limited to considering only centralized and decentralized ACSs of microgrids. Ref. [24] provided a comprehensive review of AC-DC microgrid control schemes, indicating the effect of the control schemes adopted on the stability of microgrids but with the scope limited to AC-DC microgrids only. Thus, the existing review articles have addressed a large number of important issues, but there remain those that will benefit from additional analysis. In other words, the existing literature reviews considered various algorithms and methods of control of microgrids, which in most cases were presented as having a simplified topology, without taking into account the technical aspects that limit their application.

This article analyzed the state-of-the-art principles of microgrid design that influence the choice of microgrid power flow control methods, as well as power flow control methods themselves. The approach adopted here allows for streamlining the process of designing microgrid ACSs in existing distribution grids' low-voltage AC and AC-DC microgrids. The article aims to discuss the principles of step-by-step design of microgrid control systems based on already-known approaches so as to prevent the improper application of algorithms and methods in the design process.

Section 2 of the article deals with the principles of design and the main types of microgrids. Section 3 describes the principles of design of microgrid control systems, highlighting the main objectives behind their creation and the requirements stipulated by the standards. In addition, we discuss the existing structures for building microgrid control systems and analyze various approaches to their implementation. Section 4 gives an overview of available algorithms and methods for controlling AC microgrids and AC-DC microgrids (hybrid microgrids). Section 5 discusses practical examples of AC microgrid and hybrid microgrid control implementations. Section 6 covers the application of algorithms and methods for controlling AC microgrids and hybrid microgrids, taking into account their optimal use. Section 7 provides recommendations for implementing microgrid control systems and outlines future research in microgrid control. Section 8 wraps up the paper with conclusions and the results of the review performed.

2. Microgrid Design Principles

Integration of microgrids into distribution systems has a positive effect on power systems in terms of improved observability, controllability, power quality, and reliability of power supply to consumers [25,26]. One of the challenges is to ensure the dynamic stability of DERs in emergency and post-emergency states, which is due to the lack of small values of T_j in DERs as this imposes restrictions on allowable load flows and control algorithms of microgrids [27]. Therefore, microgrids must operate as subsystems within the distribution grid control system. Subsystems must have a structure that meets the requirements for ACSs of DERs in order to maximize their technical and economic performance.

2.1. Ways to Integrate DERs

The effective use of different DERs with heterogeneous characteristics is only possible with predefined and standardized procedures for forming microgrids. In what follows we consider the DC, AC, and AC-DC circuits used in the design of microgrids [28,29]. Discussions about the predominant use of one or another circuit have continued until recently [30]. Lessons learned from designing microgrids indicated that the determining factor is the type of current consumed by electrical loads, most of which are powered by an alternating current. It is converted from alternating current to direct current in a number of electrical loads, such as electric cars, lighting systems, ESSs, etc. All DERs can be divided into two groups with respect to the way they are integrated into microgrids. The first group is the DERs that are coupled directly, not requiring the use of power converters. The group includes GGSs, DGSs, and wind turbines of the first, second, and third types [31]. The second group includes DERs integrated through inverters (converters). This group includes PV modules, Type 4 wind turbines [31,32], microturbines, ESSs, and fuel cells. Therefore, AC operation is preferable for the former group and DC operation for the latter. This eliminates the power converter from the circuit, which helps reduce power losses and capital costs, and increases the reliability of DERs.

2.2. Optimal Structure of DERs in Microgrids

Key defining features of microgrids include the large-scale integration into them of renewable DERs, as well as heterogeneous loads with intermittent power generation/consumption. This can cause short-term unbalances of active and reactive power, which leads to decreased power quality parameters and unstable operation of microgrids [33,34]. To solve this problem, it is effective to use ESSs, but the capital and operating costs of ESSs remain high. It is required to determine the allowable power of renewable DERs as part of microgrids, as well as the optimal power and energy capacity of ESSs [35].

A proper design is paramount to the reliability of microgrids because when they operate in the islanded mode it allows them to maintain the specified power quality parameters with respect to voltage and frequency. To model uncertainties when scheduling microgrid power flows, it is proposed to use a probabilistic power flow, usually calculated by Monte Carlo simulation, which is computationally expensive [36]. An alternative to the above method is the use of approximated and improved iterative algorithms [37], which have good accuracy in estimating variables and probabilistic parameters while requiring much fewer computational resources.

Selecting an optimal structure of DERs in microgrids should be backed by statistical data on load profiles on different days (weekdays, weekends, holidays), values of economic performance metrics of DERs, geographical conditions of DERs location, values of reliability metrics of DERs, etc., as well as requirements for power supply reliability and power quality [38,39].

The use of optimization methods with life cycle cost minimization serving as the criterion makes it possible to determine the allowable capacity of renewable DERs, ESS specifications, as well as the microgrid design scheme [40]. Various methods can be used in the optimization process, the most common are methods based on heuristic algorithms, mathematical programming algorithms, and interior points methods [38]. As a rule, it is possible to achieve the stated goals by using equipment with extensive power flow control capabilities as part of microgrids [40–42].

2.3. Switching Equipment of Microgrids

Microgrids can be integrated into medium- and low-voltage distribution grids, but they are most often connected to low-voltage grids, given the widespread use of PV modules in households. Microgrids are connected to a point of common coupling (PCC) by means of a static switch. The static switch position determines the mode of microgrid operation (grid-connected or islanded) and implements the transition between them [43,44]. The static switch is a fast-acting switching device based on power semiconductor components, such as triacs, which have high overload capacity [45].

Smart circuit breakers are used to provide high-speed control of DERs and critical loads. To control non-critical loads, it is standard circuit breakers with external control that are used more often [46].

2.4. Microgrid Structures

The optimal choice of the microgrid structure reduces power losses and grid modernization costs, ensures efficient frequency and voltage control in the islanded mode, and improves the reliability of power supply to consumers [30]. There are three main structures of microgrids: DC, AC, and AC-DC microgrids [47].

2.4.1. DC Microgrids

Coupling of DERs into microgrids without the use of power converters eliminates power losses that occur in their conversion in the amount of 10–25% [48]. Another advantage of DC microgrids (Figure 1) is that they maintain the values of power quality parameters within the required range, regardless of the AC grid mode of operation [28,49].

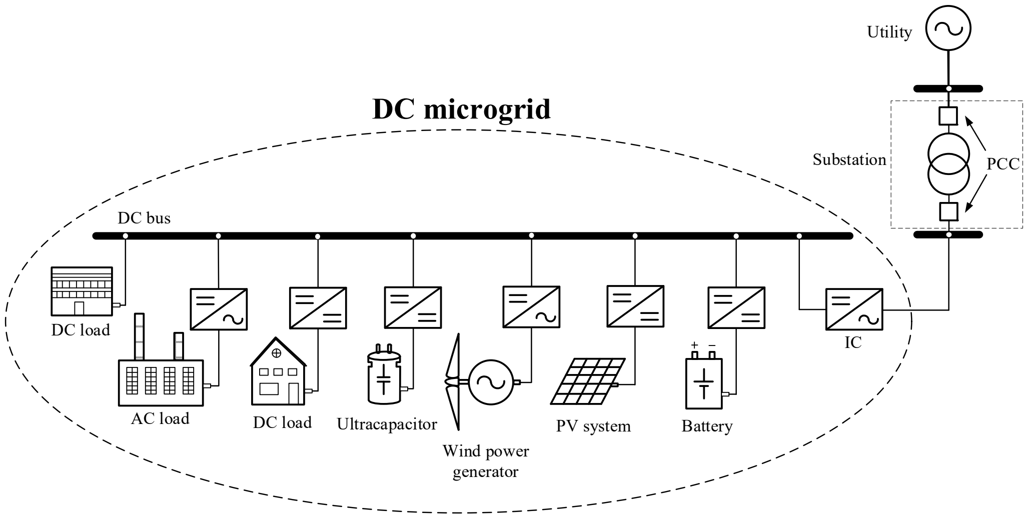

Figure 1. DC microgrid structure.

DC microgrids are integrated into the distribution grid through a bi-directional interlinking converter (IC). It provides bi-directional power transmission and galvanic isolation of DC and AC grids. DERs are connected through AC-DC or DC-DC power electronic converters (PEC) to maintain the DC voltage within the required range.

The transition of DC microgrids into the islanded mode takes place in the event of disturbances in the AC grid when the DC grid voltage deviates by more than ±10%, and there are ripples of more than ±5% [50].

The advantages of DC microgrids include a simple structure, lower construction costs, independence from the AC grid power flow, ability to maintain the required values of power quality parameters during AC grid accidents, easy voltage regulation, no reactive power, lower power losses, and no need for a synchronization algorithm in the ACS of microgrids.

The downsides of DC microgrids are the need to build a DC grid, the difficulty of integration into the existing AC grid, and the implementation of protection functions due to the lack of standards and hands-on experience [51,52]. Moreover, DC microgrids require the use of special-purpose DC circuit breakers for high fault currents, electric motors are impossible to integrate without the use of AC-DC PECs, reliability of power supply to consumers is compromised due to the presence of a common IC.

2.4.2. AC Microgrids

The availability of existing AC grids makes it much easier to create microgrids based on them. The microgrid structure proposed in the CERTS Microgrid Concept [53] is commonly used. It provides the ability to switch microgrids to the islanded mode while maintaining the power supply to the load. In this case, the main circuit breaker is connected to the substation low voltage bus, and all DERs are connected to the microgrid via DC-AC and AC/DC-DC/AC PECs [54,55] (Figure 2).

Figure 2 shows that there are three feeders in the microgrid: feeder 1 and feeder 2 serve the critical load, and feeder 3 serves the non-critical load. The installed circuit breakers allow the microgrid to be reconfigured to balance active and reactive power. The static switch controls the mode of operation of the microgrid with the distribution grid, providing switching to/from the islanded mode. Criteria for the switching of microgrids into the islanded mode are frequency deviations of ±0.2 Hz and voltage deviations of ±5%, as well as overcurrent of the transmission line equal to 30% [56,57]. In the islanded mode of operation, critical loads are fed from DERs, and non-critical loads are fed from the external distribution system.

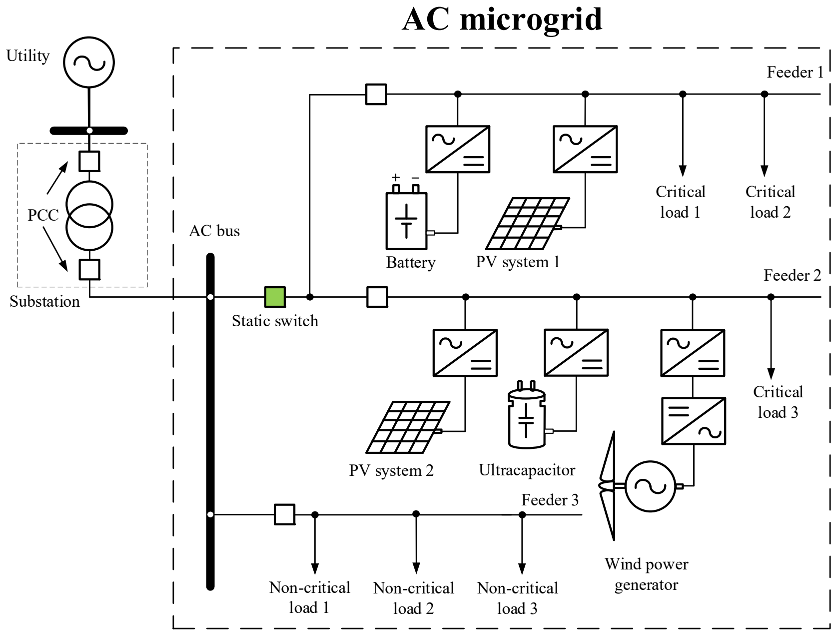

Figure 2. AC microgrid structure.

The operation of microgrids in the grid-connected mode contributes to the reliability of power supply to consumers and facilitates load dispatching of DERs during load surges/shedding [58]. The disadvantages include the presence of a large number of PECs, which compromises the reliability and efficiency of AC microgrids. There are engineering solutions that are known to improve the reliability of PECs, but their adoption is not ubiquitous [59].

Considering the above, the AC microgrid structure is most in demand for integrating DERs into existing distribution grids.

2.4.3. Hybrid (AC/DC) Microgrids

The joint use of DC and AC microgrids allows for a better structure of a hybrid AC-DC microgrid to be implemented. This simplifies the integration of different DERs and DC and AC consumers and contributes to the efficiency of their operation [28]. This case is shown in Figure 3.

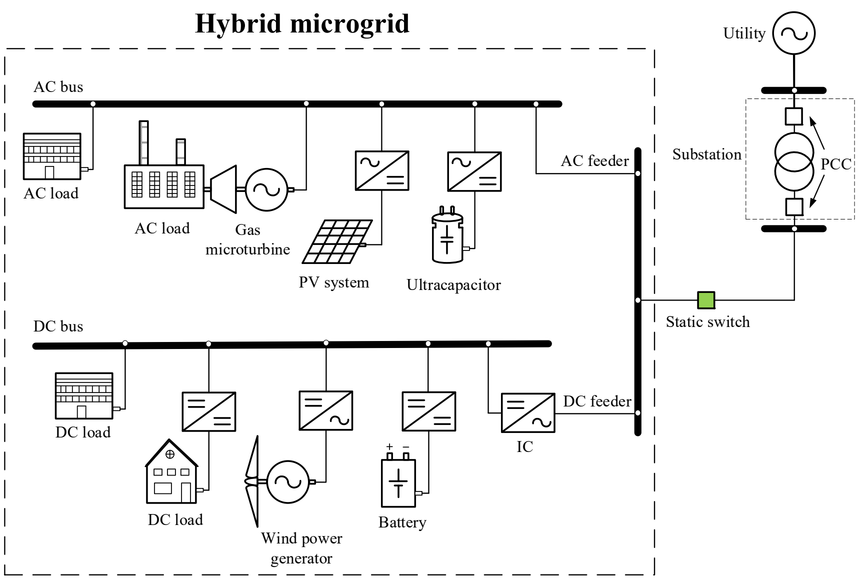

Figure 3. Structure of the AC-DC microgrid.

In a hybrid microgrid, AC consumers are connected directly to the AC bus and DC consumers through DC-DC PECs to adapt the voltage level at the bus to the voltage level of the load. Connecting DERs and DC loads to the DC bus minimizes the effect of harmonic content on the power quality parameters of the external distribution grid. Hybrid microgrids reduce the total number of PECs, which helps reduce power losses and improve the reliability of microgrids.

Creating a hybrid microgrid requires considerable expenses to build a DC grid and install a static switch to connect the microgrid to the external distribution grid. It breaks even faster as the number of DC DERs that are connected grows, because of the decreasing number of PECs. At the same time, the task of controlling a hybrid microgrid becomes more complicated due to the need to coordinate AC and DC grid control algorithms.

Hybrid microgrids combine the main advantages of DC and AC microgrids, allowing for the optimal use of different DER technologies [60]. The hybrid microgrid structure shown in Figure 3 is one of the possible topologies. Other structures differ in the way AC-DC microgrids are connected, using one or two static switches connected in parallel [55,61,62]. In addition, they can use power routers, solid-state transformers, and small-sized flexible AC transmission systems. However, in hybrid microgrids it is recommended to use a semi-regulated high-frequency resonant DC transformer, operating at a resonant frequency, which provides the required active power transmission ratio with a constant voltage conversion gain [63].

3. Design Principles of Microgrid ACS

One of the main tasks of creating ACSs of microgrids is to ensure optimal control of electricity production and consumption, as well as the sale of electricity as governed by market mechanisms. This enhances the investment appeal of microgrids acting as aggregators of DERs as well as adjacent microgrids [64].

3.1. Tasks of Microgrid Control

The grid-connected and islanded modes of microgrids both have their unique features in terms of control arrangement. In the former mode, the frequency and voltage are determined by the external distribution grid, and in the latter mode, by the frequency-operated generation unit. In addition, it is necessary to ensure bumpless transfer from one mode to the other and back [65,66].

In the grid-connected mode, the tasks of maintaining the voltage at nodes, overload management, reduction of power losses, as well as maintaining the required values of power quality parameters (reduction of voltage sags, harmonic compensation, flicker mitigation, etc.) are solved. Furthermore, the control of power flows between the microgrid and the external distribution grid by controlling the load of DERs is implemented, as well as a bumpless transfer from the grid connected to the islanded mode by the action of automatic multiparameter partitioning devices [67].

Operation in the islanded mode solves the following problems:

- frequency and voltage regulation within a specified range for all topologies and operating conditions by controlling the active and reactive power of DERs, while respecting the available constraints;
- automatic synchronization with the external distribution grid when the load flow parameters are normalized there;
- electricity sales based on market mechanisms through optimized load dispatching of DERs;
- reliable power supply to critical loads as part of the microgrid for all topologies and operating conditions;
- automatic "black start" of microgrids in case of blackout;
- optimization of operating costs for the generation and distribution of electric power to consumers [68,69].

The above tasks are divided into groups. These groups of tasks [70] are addressed at three levels: the local level, the microgrid level, and the level of an external distribution grid (Figure 4).

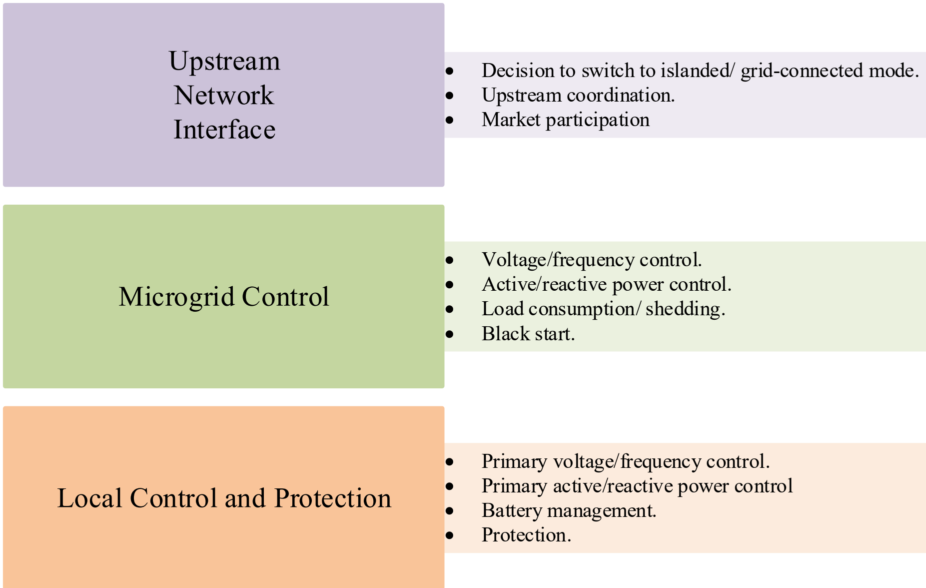

Figure 4. Separation by the level of tasks completed in the operation of microgrids.

The following features should be taken into account when completing control tasks:

- power flows: bi-directional power flows occur between microgrids and the external distribution grid, depending on the modes of generation of DERs and consumption within microgrids;
- stability: short-term fluctuations in power flow parameters can occur due to the interaction of different ACSs, as well as when microgrids switch from the grid-connected mode to islanded mode;
- low inertia: the dynamic characteristics of DERs, especially of those connected through PECs, differ significantly from the characteristics of high-power generation units coupled directly. Low inertia in microgrids and lack of the spinning reserve can lead to significant frequency and voltage deviations in the islanded mode;
- uncertainty: it results from the intermittent demand and generation of electricity by renewable DERs, which requires the ACS of microgrids to factor in the current value of generation, predicted electricity demand, and its price to ensure reliability and cost-effectiveness.

Since microgrids have the features that make them stand apart, their design principles should be adapted to the specified operating conditions, which differ from conventional ones in distribution grids (load balance across phases; load constancy; X/R ratios of transmission lines) [71,72].

3.2. Requirements for ACSs of Microgrids

A large number of topologies and operating conditions of microgrids require the design of more advanced ACSs [73]. The creation of service-oriented ACSs is possible through the use of modern information and communications technology infrastructure, intelligent electronic devices, and integrated hardware and software systems [74].

Table 1 [75] lists the regulatory documents containing technical requirements and recommended practices. These documents should be used for the design and operation of microgrids as well as their ACSs, depending on the characteristics of microgrids (capacity; topology; types of DERs; load mix).

Table 1. Standards for the design of microgrids.

Application Scope	Standard	Short Description	Reference
Electrical Safety	IEC 60364-1 «Low-voltage electrical installations—Part 1: Fundamental principles, assessment of general characteristics, definitions»	Recommendations for design and verification of electrical installations of nominal voltages up to 1000 VAC or 1500 VDC to guarantee the safety	[76]
Electromagnetic compatibility	IEC 61000-4-30 Electromagnetic compatibility (EMC)—Part 4–30: Testing and measurement techniques—Power quality measurement methods»	Requirements for power quality boundaries for AC and DC buses (e.g., voltage unbalance is limited to 3%)	[77]
Design of systems with DERs	IEC 61508 «Functional safety of electrical/electronic/programmable electronic safety-related systems»	Features of the design of electrical, electronic, and programmable systems that provide the required reliability, efficiency, and fault-free operation of microgrids with DERs	[78]
Structures for control system design	IEC 61499 «Function blocks»	Distributed control structure; standardized requirements for software tools to ensure software compatibility in intelligent devices, machines, and systems	[79–81]
Creation of a general information model	IEC 61970 «Energy management system application program interface (EMS-API)»	Requirements for the general information model, equipment, and other components of the power system in the form of classes, their properties, and links	[82]
	IEC 61968 «Application integration at electric utilities—System interfaces for distribution management»	Requirements for exchanging asset management, work scheduling, and billing data for consumers in microgrids	[83]
Connecting microgrids to the public grid	IEEE 1547 «Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces»	Rules for the safe integration of DERs (up to 10 MVA), allowable load flows during microgrid switching to the islanded mode, and requirements for power quality boundaries. Standardized values of U, f, and phase angle at the interface point	[56]
Power utility automation	IEC 61850 «Communication networks and systems in substations»	Rules for the communication between microgrids and substations, as well as intelligent devices within microgrids	[84]
Information security	IEC 62351 «Power systems management and associated information exchange—Data and communications security»	Requirements for information security (data transfer and communications design)	[85]
Power System Management (PSM)	IEC TR 62357 «Power systems management and associated information exchange»	Requirements for power system management processes and related information exchange	[86,87]

Table 1. *Cont.*

Application Scope	Standard	Short Description	Reference
Energy Management System (EMS)	IEEE Std P2030 «Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads»	EMS-based control layer functions that are common to all microgrids, regardless of their structure, topology, or affiliation	[88]
Stand-alone DC power suppliers	IEEE 2030.10 «Standard for DC Microgrids for Rural and Remote Electricity Access Applications»	The rules of operation of 48 VDC microgrids in self-sustaining communities. Recommendations on DC grid control and communication protocols	[89]
Medium voltage DC bus	IEEE 1709 «Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships»	Recommendations for maintaining power quality parameters in 1000 V to 35,000 V grids within specified boundaries (e.g., maximum acceptable ripple and DC voltage tolerances)	[50]
Energy thermal efficiency of buildings	ISO 52016-1 «Energy performance of buildings—Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads—Part 1: Calculation procedures»	Response time requirements in low-voltage AC microgrids to meet thermal performance requirements for buildings (e.g., energy requirements for heating and cooling)	[90]
Connection of electric vehicles	IEC 61851 «Electric vehicle conductive charging system—Part 23: DC electric vehicle charging station»	Information about household electric vehicle charging stations in single-phase (250 V) and three-phase (480 V) systems	[91]

3.3. Structures of Microgrid ACSs

It is impossible to create a standardized design of a microgrid ACS [70]. This is due to the wide variety of DERs, microgrid structures, types of electrical loads, etc. Therefore, the structure of an ACS is formed on a case-by-case basis for each microgrid during its design.

The same approaches are used in the design of microgrid ACSs as those in the ACSs of power systems. The distribution management system (DMS) is commonly used in distribution grids. The DMS implements algorithms for monitoring the grid and DERs, as well as those of grid reconfiguration and voltage regulation by controlling static reactive power compensators and the largest generation units. However, the DMS does not provide for the implementation of control actions on multiple DERs, which leads to compromised reliability of distribution grids. When DERs are deeply integrated, controllability can only be achieved by creating more advanced ACSs of microgrids [92].

The microgrid structure usually has a central controller as well as controllers of DERs. Most often local controllers that combine their functions are used instead of the latter [93–96].

Local controllers come either as separate devices or as a set of functions in intelligent electronic devices (smart meters, PECs) with sufficient computing power. Local controllers implement algorithms for monitoring and control, including the control of the power of DERs, through control actions on PECs.

Information and communications technology infrastructure are not necessary for local controllers to function. They implement decentralized algorithms based on frequency and voltage droop control. This allows for the DERs power control based on local data, since the frequency is related to active power and voltage is related to reactive power [93]. This approach is applicable to DERs based on synchronous generators, but its implementation in DERs with PECs is not possible, given the features discussed below.

The central controller coordinates local controllers in the microgrid to improve technical and economic performance by implementing ancillary services and ensures microgrid communication with the energy service company and distribution system operator. In addition, the central controller calculates and issues setpoints and control actions to local controllers. The central controller is usually designed as a separate unit installed in the medium voltage substation but is sometimes integrated into the DMS [70].

3.3.1. Hierarchical Control in Microgrids

A large number of different DERs with different protection setpoints and allowable operating ranges influence the nature and parameters of transients, which determines the requirements for control algorithms in ACS microgrids [97]. It is important to note that the different control algorithms are decoupled in time, since they require to be executed in a certain sequence. Therefore, in microgrids, ACSs with a hierarchical structure, which is also standardized, are widely used [98].

Hierarchical ACSs can have a different number of control levels. The most common are the three-level ACSs:

- primary level: power, voltage, and current monitoring of DER. The level implements the basic algorithms with setpoints specified by higher-level controllers via PECs [99];
- secondary level: monitoring of the execution of algorithms on the first level and maintaining the required values of power quality parameters in the microgrid [100]. The level implements algorithms for microgrid switching from the grid-connected mode to islanded mode and back, as well as control of the amount of power flows to and from the external distribution grid (other microgrids);
- tertiary level: implements optimization algorithms to improve the economic performance of microgrid operation. This requires information and communications technology infrastructure, as well as intelligent algorithms for decision-making [101].

Thus, the tasks of power supply reliability and power quality are implemented at the primary and secondary levels, and economic performance is ensured at the tertiary level of control.

Separating control tasks by the time of their execution streamlines the analysis of microgrid behavior, as well as modeling and forecasting processes. The transition to higher-level tasks is accompanied by a decrease in the speed of algorithm execution [102] (Figures 5 and 6).

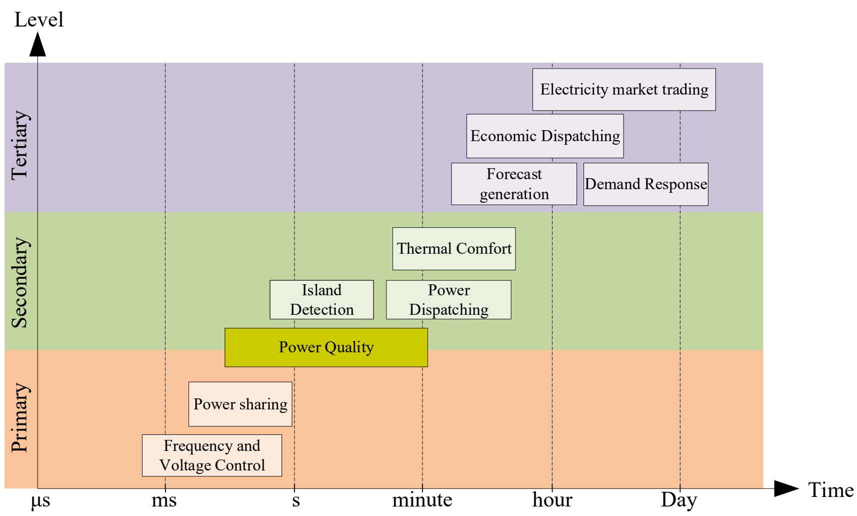

Figure 5. Timeline of the execution of main control algorithms in microgrids.

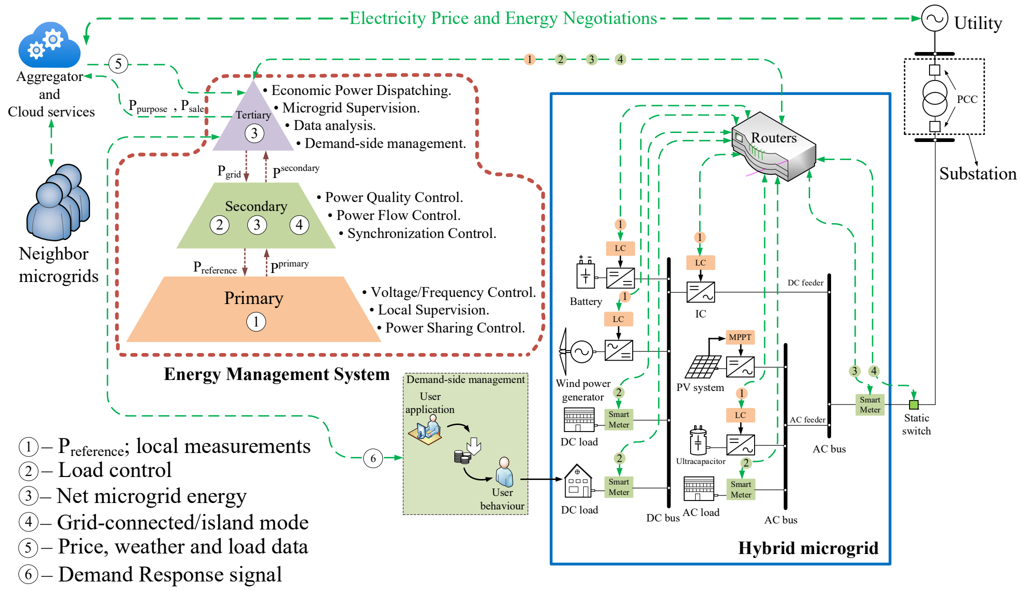

Figure 6. Hierarchical control of AC-DC microgrids in a building.

Coordinated management of DERs in microgrids can be implemented using centralized, decentralized, or distributed approaches to control (Figure 7). The choice of a particular approach is determined by the goals of the creation of the microgrid and the specifics of microgrid design, as well as the availability or accessibility of resources (personnel, equipment, etc.).

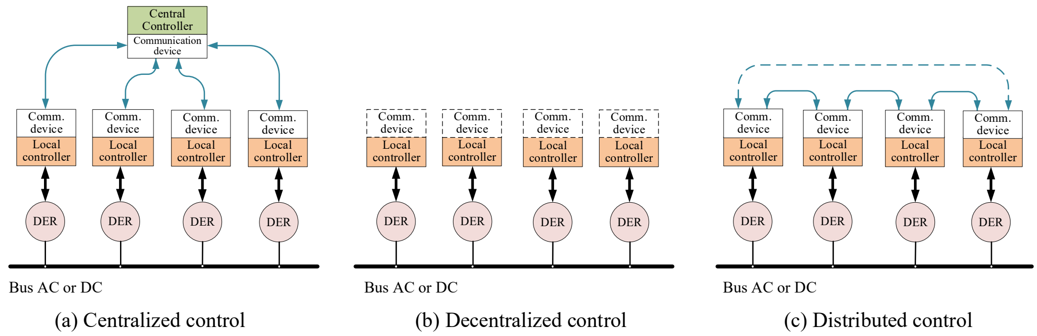

Figure 7. Approaches to microgrid control.

The degree of decentralization of control in microgrids depends on the functionality, the control algorithms implemented, as well as the computing power of local controllers.

3.3.2. Centralized Control of Microgrids

The centralized approach to the arrangement of microgrid control (Figure 7a) is well-researched because its implementation is based on the same principles as in the hierarchical ACS. In the case of centralized control, all control functions are implemented in the central microgrid controller, which analyzes the information from local controllers of DERs and calculates and issues the control actions. The control actions are implemented by local controllers, whose functions in AC and AC-DC microgrids are often performed by PECs.

Achieving maximum efficiency in microgrids is possible through coordinated control of all DERs, which is attainable when centralized control is implemented. More DERs operating in a microgrid require more processing power from the central controller, so this approach to control is used in small microgrids.

Having one device performing all calculations in a microgrid requires reliable high-speed broadband communication links between local controllers and the central controller.

However, this does not guarantee high reliability of the entire ACS, since the employed topology of the communication network (point-to-multipoint) in case of failure of the communication interface of the central controller, leads to a complete failure of the ACS.

3.3.3. Decentralized Control of Microgrids

In the decentralized approach (Figure 7b), all control functions are implemented in local controllers using only local information. There is no need for a central microgrid controller and information and communications technology infrastructure. There is implicit communication between the local controllers. It is due to the mutual influence of the results of the implementation of algorithms by individual local controllers on the change of load flow parameters in the microgrid. This reduces the computational load on the local controllers since the completion of the control task is divided among the individual components.

3.3.4. Distributed Control of Microgrids

The presence of two-way communication between neighboring local controllers allows for the creation of the distributed ACS of microgrids (Figure 7c) to maximize the effect of optimization algorithms.

The partial mesh topology of the communication network used in distributed control allows it to remain operational in case of failure at any node. This communication network topology simplifies the process of scaling it up since each individual node is essentially a router. When connecting new DERs, it is not necessary to reconfigure the communication network, and this allows for the use of plug-and-play technology. The distributed control approach is more attractive than the centralized approach, presenting a holarchic control architecture [103] with a holonic production system [104].

The hybrid approach to microgrid ACS implementation is to combine local controllers of one cluster (several DERs connected close to each other) under the control of one central controller connected to the central controller of another cluster in the microgrid. This improves the coordination and efficiency of DER control in both grid-connected and islanded modes [105].

4. Algorithms and Control Methods for Microgrids

4.1. Control Methods for PECs

Ref. [30] provided recommendations for the choice of structures and methods of microgrid control using different communication links. The choice should take into account the structure of the grid as well as the allowable power flows of microgrids. Existing studies addressed the issue implementation techniques of bumpless switching to the islanded mode, as well as those of economic scheduling, joint regulation of frequency and voltage, improving the reliability of redundancy, preventive and emergency control, synchronization and execution of automatic "black start" have been studied. Ref. [106] reviewed practical examples of the construction and operation of microgrids based on a hierarchical ACS.

Creating microgrids requires solving optimization problems, which fall into three classes: optimal power flow, scheduling, and planning. Various metaheuristic methods have been most widely used for their solution, since they show good results for solving complex control problems, especially those characteristics of microgrids with intermittent generation [107].

Metaheuristic methods include:

- evolutionary computations: methods that simulate the evolution of population members (genetic algorithms, differential evolution);
- methods of swarm intelligence: methods capturing the properties of self-organizing groups of biological organisms with "smart" global behavior (ant colonies, harmony search algorithm, particle swarm optimization, etc.);

- artificial immune systems: methods inspired by theoretical immunology and modeling the processes used by the immune system to respond to external threats;
- non-population-based metaheuristics: methods based on finding a single solution, i.e., temporarily taking the worst solution with a probability that decreases as more iterations are run (simulated annealing, tabu search) [108].

The choice of the metaheuristic method is based on the available computational resources and the number of function convergence estimates [109]. For example, evolutionary computations based on genetic algorithms are applicable to any configurations of microgrids, allow the use of hybrid approaches, are easily scalable, and do not impose restrictions on the functions they perform. However, the performance of the algorithm is determined by the quality of the coding of the optimization problem, as well as by its sensitivity to parameter setting [110]. The differential evolution method, which has a higher rate of function convergence than the genetic algorithm, is a simple and reliable method applied to optimization problems with constraints that require a relatively small number of control variables. However, this algorithm strongly depends on parameter setting, which determines the convergence rate [111].

Issues with coding the algorithm are resolved due to the use of swarm intelligence methods, such as the particle swarm optimization method. This method does not require special coding, and its simplicity combined with efficiency makes it an ideal solution when computational resources are limited [111].

Artificial immune systems are formed on the basis of a distributed model with no control center, i.e., they use only local information. Therefore, these methods require a minimal amount of computational resources, unlike population-based methods. However, these methods require calibration to solve the optimization problem, unlike evolutionary computation and swarm intelligence methods [112].

Non-population-based metaheuristic methods require the least computational resources relative to other methods, but they also have the lowest accuracy [113].

The studies and examples reviewed here show that the key challenge is to ensure the proper operation of the static switch through which the microgrid communicates with the external distribution grid. In the grid-connected mode of operation, it must function as a current source, providing power output and consumption from the external distribution grid, and in the islanded mode, as a voltage source, creating a reference voltage of nominal frequency for the microgrid [114].

4.1.1. Switching Microgrids to the Islanded Mode

The main difficulties in the implementation of the ACS of the static switch are time delays that occur both in the dynamic response of the ACS and during its operation. Compensators of voltage, active and reactive power are used to stabilize the external characteristics of the static switch [115]. For example, when the microgrid switches to the islanded mode, deviations are possible between the actual and reference voltage values of the DC link static switch, in which case the output voltage compensator that sets the reference current for the internal control loop is triggered [14].

4.1.2. Operation of Microgrids in the Islanded Mode

Switching of microgrids to the island mode takes place either in case of accidents or during scheduled switching operations in the external distribution grid. Since the main circuit breaker of the microgrid has high speed, the transfer to the islanded mode requires rapid coordination of control algorithms of all DERs with PECs in the microgrid, so the ACS needs to implement an algorithm to control microgrid operation modes.

The main goals of microgrid islanded mode control are as follows [116]:

- maintaining the necessary voltage value at the voltage source in the microgrid to ensure proportional power allocation between DERs with PECs;
- maintaining the specified frequency at the voltage source in the microgrid, according to the specified characteristic and droop coefficient.

4.1.3. Synchronization of Microgrids with the External Distribution Grid

The main method used to synchronize microgrids with an external distribution grid is the phase-locked loop technique [117]. In this technique, the phase angle of the voltage vector is selected based on the microgrid voltage vector and the q-axis voltage vector at the point of common coupling. Then, using a phase-locked loop, the angle between these vectors at the voltage source is reduced to zero.

However, the phase-locked loop technique cannot be used in the presence of an unbalanced (non-linear) load, as it is a source of interference to the execution of the algorithm. Its operation provokes sudden changes (jumps) in the phase angle. In this case, a modified phase-locked loop method should be used, which additionally uses a second-order generalized integrator to adjust frequency [118]. To coordinate local microgrid controllers relying on voltage and current control algorithms, as well as the phase-locked loop technique, it is necessary to provide for the implementation of control actions from the central microgrid controller or apply other methods [119].

4.2. Features Unique to Microgrid ACS Implementation

4.2.1. AC Microgrids

The microgrid ACS usually has a three-layer hierarchical structure. Primary control in microgrids is implemented by local controllers acting on PECs of DERs, providing control of their active and reactive power and allocation of power among DERs.

Control of DERs is implemented by algorithms that fall into several categories, depending on the selected current and voltage reference system: synchronously rotating system dq, complex system $\alpha\beta$, and natural three-phase system abc [120]. In a synchronously rotating system, proportional-integral (PI) regulators are used, in a complex system, proportional-resonance (PR) regulators are used, and in a natural three-phase system, PI or PR regulators are used. Output parameters of DERs are controlled through an external loop (for voltage control) and an internal loop (for current control). Traditionally, linear and nonlinear current regulators are used for this purpose [121].

Linear current controllers are used in PI controllers in DC grids because they can track specified values with zero steady-state error. On the other hand, PR controllers are most often used for control in AC grids.

Non-linear current regulators are based on hysteresis current control, sliding load flow control, neural network algorithms, and fuzzy logic algorithms. Thus, nonlinear regulators control the active and reactive power of DERs by regulating the current in the DC link of PECs. Various problems may arise, which were discussed in detail in [122].

The most common method for controlling PECs of DERs are multi-parameter methods and their various modifications, which improve the dynamic response when the microgrid load flow changes and increase the tolerance to load uncertainty (non-linearity) [123–126].

Managing the allocation of power between DERs helps ensure the reliability of power supply to consumers and the optimal operation of microgrids. To this end, droop-based methods as well as methods that do not use droop are employed.

The droop is specified by the P-f and Q-f characteristics in order to regulate the frequency and voltage in the microgrid islanded mode [127–131]. If $U_{mg} < 0$ and $E < \delta$ when integrating DERs through PECs with a small value of the angle δ, the magnitude of active and reactive power when connected to a transmission line with predominantly inductive reactance will be determined by Equations (1) and (2):

$$P = \frac{U \cdot E}{X} \cdot \delta; \tag{1}$$

$$Q = \frac{U \cdot E - U^2}{X}, \tag{2}$$

where U is the PEC output voltage; E is the voltage at the point of common coupling.

Given that in low- and medium-voltage power lines the ohmic resistance prevails, expressions (1) and (2) are not applicable for these grids. The *P-f* droop characteristic reduces the output voltage frequency with increasing output power of PECs of DERs, while the *Q-f* droop characteristic reduces the output voltage amplitude with increasing reactive power in the microgrid islanded mode.

Specifying the droop allows one to simulate the inertia of the synchronous machine for DERs with PECs in order to maintain the balance of active power and frequency in the islanded mode. In case of emergency disturbances, significant deviations of frequency and voltage from the nominal values may occur, which leads to instability of regulation. For voltage sources, the frequency and voltage values are set according to Equations (3) and (4):

$$\omega = \omega_0 - D_1 \cdot P; \tag{3}$$

$$U = U_0 - D_2 \cdot Q, \tag{4}$$

where ω_0—nominal angular frequency at the voltage source; U_0—nominal output voltage of the voltage source; D_1 —droop constant for the *P-f* characteristic; D_2—droop constant for *Q-f* characteristic. They can be specified: $D_1 = \frac{\omega_{max} - \omega_{min}}{P_{max}}$ and $D_2 = \frac{U_{max} - U_{min}}{Q_{max}}$, where ω_{max} and ω_{min} are the maximum and minimum angular frequency values; U_{max} and U_{min} are the maximum and minimum voltage values; P_{max} and Q_{max} are the maximum allowable values of active and reactive power of DERs.

The disadvantages of traditional droop-controlled methods were discussed in detail in [130]. Some of the difficulties can be solved by modifying the techniques. Next, we consider modified techniques for setting droop [131] relying on the following:

- static characteristic of voltage regulation as a function of active power (U-P_s) and inverse static characteristic of frequency regulation as a function of reactive power (f-Q_{is}) [132,133]; static characteristic of reactive power regulation as a function of voltage increment *Q-U′* [134]; static angle regulation [135];
- transformation of the reference frame [136];
- virtual impedance [137,138], virtual inertia [139,140];
- unbalanced control of active and reactive power flows and non-linear load dispatching [141–143];
- adaptive (modified) droop control [144,145].

In what follows, we consider the principles of their implementation, as well as the advantages and disadvantages.

Static characteristics of voltage regulation as a function of active power (U-R_s) and inverse static characteristics of frequency regulation as a function of reactive power (f-Q_{is}) are used in low-voltage grids. In this case, the output voltage of PECs of DERs decreases as the output power increases, while the frequency increases as the output reactive power increases. This improves the power allocation in low-voltage grids but it depends on the parameters of the grid. This approach is not applicable to grids with non-linear loads.

The static characteristic of reactive power regulation as a function of the voltage increment *Q-U′* provides reactive power allocation between DERs regardless of the transmission line impedance. The voltage restoration circuit maintains a constant output voltage by maintaining a zero-voltage increment $U' = 0$. This method depends on initial conditions and also has low stability.

Static angle regulation has a significant low-frequency deviation compared to static frequency regulation. The angular phase of the PECs output voltage can be used effectively, provided that low bandwidth communication links are in place. However, the method requires inductive reactance between the PECs and the microgrid AC bus. A larger angle enhances the droop effect through an additional control loop in low-power microgrids in order to increase the accuracy of load allocation between DERs.

The reference system transform method uses a linear orthogonal matrix to convert the values of active and reactive power flows to a new reference system, where they do not depend on the transmission line impedance. In Equations (3) and (4), P and Q are substituted for the transformed P_n and Q_n, respectively. Similarly, the frequency and amplitude of the output voltage are transformed into the variables ω_n and E_n, which form the PECs reference voltage and frequency for the control circuits.

The virtual impedance is used in the feedback circuit of the voltage regulation loop. Thus, the PECs output voltage is generated by adjusting the virtual impedance $Z_u(s)$. The output voltage of PECs (U) is defined as $U = U_0^* - Z_u(s) \cdot i_0$, where U_0^*—output voltage of PECs at no-load; i_0 —output current; Z_u —virtual impedance. If $Z_u(s) = sL_u(s)$, the output voltage decreases in proportion to the derivative of the output current. However, the harmonic distortion of the output voltage will have large values when feeding a non-linear load. To solve this problem, one has to use a high-pass filter instead of sL_u.

The emulation of virtual inertia in microgrids prevents nuisance tripping of circuit breakers during short-term frequency decreases/increases. The droop coefficient is modified as the function $\frac{df}{dt}$, which is effective when $\frac{df}{dt}$ exceeds the threshold value B. The rule of the modified droop control method takes the form:

$$\omega_i^* = \omega_n - c_i \cdot (P_{n,i} - P_i), \tag{5}$$

where ω_i and P_i—voltage frequency and output active power of DERs, respectively; indices "*" and "n"—reference and a nominal number of PECs; c_i—droop coefficient, determined by Equation (6):

$$c_i = \begin{cases} c_{n,i} - \omega_1 \cdot \left|\frac{df}{dt}\right|^{\omega_2}, \text{ for } \left|\frac{df}{dt}\right| \geq B \\ c_{n,i}, \text{ for } \left|\frac{df}{dt}\right| < B \end{cases}, \tag{6}$$

where $c_{n,i}$—nominal droop gain, which changes if the rate of frequency change exceeds the set value; ω_1 and ω_2—frequencies corresponding to the maximum PECs power and the maximum allowable frequency change, respectively.

The virtual inertia emulation allows us to represent the voltage source as an equivalent virtual synchronous machine (VSM) with a static frequency control characteristic in microgrids [140] (Figure 8).

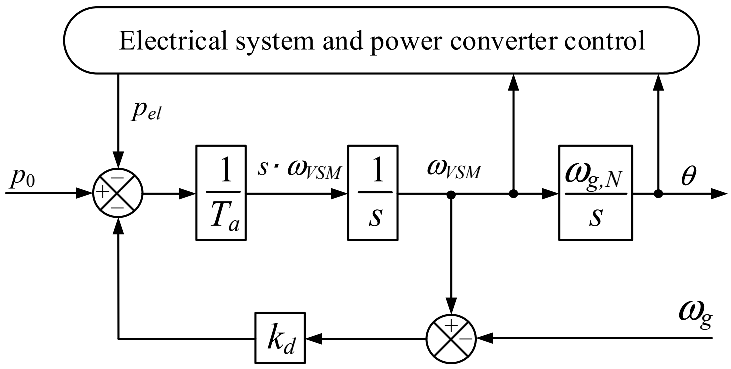

Figure 8. Emulation of inertia by a virtual synchronous machine.

Low-pass filtering of active power in the voltage source circuit also contributes to virtual inertia, which improves stability and damping in microgrids. Simplified frequency droop control P-f is implemented as per Equation (7):

$$T_f \cdot \frac{1}{m_p} s \cdot \omega^* = P_0 - P_f - \frac{1}{m_p}(\omega^* - \omega_g); \tag{7}$$

where $P_0 = p_0$—reference value of active power; T_f—time constant of the low-pass filter; $P_f = p_{el}$—filtered output active power; $m_p = 1/k_d$, m_p—frequency droop coefficient; k_d —damping coefficient of active power regulator; ω^*—reference value of angular frequency;

ω_g—angular frequency at the point of connection to microgrid; p_m—active power signal in the feedback link; θ—angular position of VSM rotor.

The negative effect of unbalanced flows of active and reactive power in the transmission line can be compensated by applying a high-frequency signal, which was discussed in detail in [141].

There is a method that provides current-sharing between the PECs of DERs connected in parallel without coupling between them [142]. There is also a technique that has harmonic voltages calculated based on the current harmonics and impedance of the PECs for each frequency. The resulting voltage is then added to the reference voltage of PECs of DERs to eliminate the effect of the harmonic voltage on the output voltage. At the same time, its value must be calculated for each frequency for compensation purposes.

There is a technique that uses a negative virtual harmonic impedance to compensate for the effect of transmission line impedance [143]. This makes it possible to share harmonic energy without deteriorating the power quality of consumer buses. Harmonic separation is achieved by reducing the transmission line impedance corresponding to a particular harmonic and by reducing the voltage that is added to the reference voltage.

Adaptive voltage droop control improves the quality of voltage regulation by eliminating the resistance between the voltage source and the point of common coupling [144]. In this case, the voltage drop across the resistance between the voltage source and the point of common coupling is included in the standard *Q*-*U* static control procedure. This method is highly effective at high loads in the microgrid, but at medium and low loads the effect of its use decreases.

Modified adaptive droop control is implemented using Equations (8) and (9):

$$\delta = -n_p P - n_i \int_{\infty}^{t} P d\tau - n_d \frac{dP}{dt}, \quad (8)$$

$$U_0 = U - jQ - j_d \frac{dQ}{dt}, \quad (9)$$

where δ—power angle and frequency calculated from power angle derivative; n_p, n_i and n_d—proportional, integral, and differential coefficients of output active power P; j and j_d—static and differential voltage droop coefficients; U_0 and U—specified (nominal) and regulated output voltage of PECs.

Modified adaptive droop control minimizes the transient circulating current between PECs of DERs, thereby improving the transient characteristic [145]. This provides the local microgrid controller with two degrees of freedom. Droop gain is used to control the magnitude of voltage and frequency, and transient coefficients are adjusted to actively suppress low-frequency power while it is shared among the PECs of DERs.

Droop is controlled by a proportional-integral-differential compensator that optimizes the frequency characteristic of the filter using three gain factors: proportional, integral, and differential. The first one is used for active power control, the second one is for power angle control together with PI reactive power compensator, and the third one is for the output voltage of PECs of DERs. Simulation results confirmed that when small signals are applied to the compensator input, they are amplified in the transient, thus improving the response of PECs of DERs.

When not using droop control, communication links between devices in the microgrid are required. To improve the efficiency of control, it is justified to adopt a centralized approach to control in microgrids as implemented in the following ways [71,146,147]:

- centralized control: local controllers transmit the data on the currents of all DERs to the central microgrid controller, which also monitors the voltage in the external distribution grid. The central controller calculates the contribution of each of the DERs to the total current, taking into account their specifications. The setpoints are also calculated from the output currents of DERs, which are transmitted from the central controller to local controllers. This approach allows for effective damping of transients but depends entirely on the reliability of the microgrid's information and communications technology infrastructure [148,149];

- "master-slave": the master PEC of the DER ensures that the microgrid maintains voltage and frequency within acceptable ranges, while the slave PECs of DERs either output or consume P and Q. This method is quite flexible, but its reliability is highly dependent on the proper operation of the master PEC of the DER under all load flows [150–152];
- voltage regulation and control of power allocation between PECs of DERs are performed by the central microgrid controller via low bandwidth communication links. In this case, local controllers provide harmonic and unbalance suppression [152–154].

Secondary control in microgrids is implemented through the EMS, which is responsible for maintaining power quality parameter values as well as frequency and voltage restoration when the primary control reserves prove insufficient [155,156]. The EMS provides synchronization of the microgrid with the external distribution grid, as well as optimal coordination of DERs in the microgrid. Secondary control can be implemented on the basis of centralized, distributed, and decentralized principles.

In centralized secondary control, the central microgrid controller sets the power values for local controllers [157]. Its main advantage is the online optimization of input parameters: setpoints, boundary conditions, network parameters, and predicted load flow.

As the number of DERs in a microgrid grows, the need to use distributed control methods arises. This allows for effective interaction between microgrid components to improve reliability, safety, and optimal performance [157]. In this case, the EMS communicates with the distributed control system by issuing its active and reactive power settings.

This is realized in a potential secondary control method that requires communication links. To this end, the central microgrid controller calculates the potential function for all PECs of DERs, minimizing its value to arrive at the specified power values.

$$\varphi_i(x_j) = \omega^{dg} \sum_{k=1}^{m_{dg}} p_k^{dg}(x_j) + \omega^{cn} \sum_{k=1}^{m_{cn}} p_k^{cn}(x_j) + \omega^{ob} p_k^{ob}(x_j), \quad (10)$$

where φ_i —potential function; x_j—measurement vector of the j-th element; p_k^{dg}, p_k^{cn} and p_k^{ob}—partial-potential measurement functions of the k-th component of the microgrid; ω^{dg}, ω^{cn} and ω^{ob}—weights of partial-potential functions.

The advantage of distributed control systems is that local controllers have more autonomy and can make decisions based on their interaction with each other. In distributed control, the control actions are formed taking into account both local load flow parameters and the microgrid operation mode as a whole [158].

Next, we consider the main categories of distributed control systems.

In agent-based systems, agents can be both physical and virtual entities, capable of responding to changes in the microgrid. Agents have intelligent algorithms that allow them to interact to solve common problems [159]. Agent-based systems use algorithms for microgrid state control, multicriteria assessment, and market competition [160]. The Java Agent Development Environment [161] is used to develop agents and ensure their coordination.

The predictive control method uses the forecast data on power consumption and generation in the microgrid, as well as the variables dependent on them [162]. This method allows one to solve multicriteria optimization problems using feedback mechanism predictions and controllable system constraints. The voltage prediction approach avoids voltage instability by controlling reactive power generation in the microgrid islanded mode.

A two-layer model of predictive control of hybrid energy complexes with renewable DERs makes microgrid operation more resilient to uncertainties [163]. When solving a problem with boundary variables, the reference settings of the on/off time of the GGS (DGS) are used, taking into account the deviations of the PV module power generation from the predicted values [164]. The calculation of the GGS (DGS) on/off time offset takes into account the microgrid state, load prediction data, and the current PV module power.

In distributed control systems, consensus-based methods can be applied to solve optimization problems to obtain a convergent solution for loading PECs of DERs. The multi-agent algorithm is implemented based on the average-consensus theorem for a group of agents that are designed to interact in the microgrid [165]. The application of the dynamic-consensus method optimizes the sharing of the negative sequence current under unbalanced load conditions.

Tertiary control is the slowest type of control, allowing for the coordination of several microgrids, so as to conform with the requirements of the external distribution grid [166,167]. When the specified values of active and reactive power are obtained from the DMS, control actions are formed within microgrids, taking into account the actual values of the generated power. The control of active and reactive power flows between microgrids and the external distribution grid contributes to solving the problem of the optimization of microgrid operation.

The application of intelligent control methods for power convert-based microgrids was discussed in a large number of studies [168,169]. One of the intelligent control methods is based on fuzzy inference, which includes:

- a fuzzifier—maps crisp (real-valued) input information into fuzzy information (fuzzy subset);
- an inference engine;
- a defuzzifier—converts the fuzzy output of the rule-based inference engine into crisp (real-valued) information to implement fuzzy inference control of the spatial vector of pulse-width modulation of the power converter. This provides the values of the magnitude and angle of the reference voltage vector needed to calculate switching moments and select switching algorithms.

The method of frequency control in primary regulation based on fuzzy inference is applicable to variable-speed wind turbines [170]. A fuzzy logic operator sets the pitch angle and power of the wind turbine inverter over the entire range of wind speeds. An advantage of this approach is that the primary power reserve is maintained independent of the current wind speed by controlling the pitch angle and torque of the generator, determined by fuzzy inference control. However, this does not take into account sudden load changes and possible damage in the microgrid [171]. The combination of fuzzy inference and swarm optimization was used to implement secondary frequency control in AC microgrids [172].

Another method of intelligent control is based on the use of artificial neural networks [173]. This method has been successfully applied to the estimation of load flow parameters, load forecasting, identification of islanding away of microgrids and switching control. Adaptive neuro-fuzzy ACS, for example, can be implemented in a frequency and voltage droop controller. This allows for the independence of ACS decision-making from the parameters of the power line and microgrid configuration, but it significantly increases the computational load [172].

Next, we list the features that are unique to ACS implementation in AC microgrids:

- selection of the type of ACS should be made on the basis of microgrid parameters (number of DERs, grid structure, etc.) and possible operating conditions;
- If ohmic resistance prevails in the power transmission line connecting the microgrid with the external distribution grid, then the ACS should use the static characteristic of voltage regulation as a function of active power (*U*-*P*) and the inverse static characteristic of frequency regulation as a function of reactive power (*f*-*Q*), which will provide the required quality of regulation;
- the ACS, which has a hierarchical structure, provides a more accurate distribution of active and reactive power between PECs of DERs, as well as the required quality of frequency and voltage regulation in microgrids;
- if there are unbalanced flows of active and reactive power in the transmission line connecting the microgrid with the external distribution grid, due to the presence of non-linear load in the microgrid, the ACS should employ state-of-the-art methods. These methods involve the following: applying a high-frequency signal, allocating

harmonic current between PECs of DERS connected in parallel without coupling between them, and adding a negative virtual harmonic impedance in order to allocate active and reactive power more accurately between PECs of DERs;

- control algorithms without communication links, which are based on frequency and voltage droop control, do not depend on the location of DERs and loads in the microgrid, but they are less efficient due to the lack of information exchange between PECs of DERs;
- ACS based on decentralized algorithms are increasingly being used because of the reduced risk of ACS failure due to damage to a single component, as opposed to centralized or agent-based ACSs.

4.2.2. Control Methods for Hybrid Microgrids

Hybrid microgrids have DC and AC networks connected to each other through a common inverter.

Refs. [14,21,24,61] listed the following challenges faced by hybrid microgrids:

- the ACS has a more complex structure and control algorithms due to the absence of a system-wide variable used for power allocation and frequency and voltage regulation;
- in the stand-alone, or islanded mode, power allocation between DC and AC microgrids cannot be ensured by droop-based algorithms;
- when there is a nonlinear load in the microgrid, it is necessary to ensure that the harmonic content power is distributed among the DERs;
- it is necessary to trade off the allocation of reactive power flows against voltage regulation at microgrid nodes under different operation conditions;
- droop control must not depend on the impedance of the power transmission line between the voltage source and the point of common coupling for optimal power allocation between DC and AC DERs;
- a hybrid microgrid requires the use of a reliable EMS to ensure reliability and the best performance;
- to provide online control of hybrid microgrid load flows, it is required to use hybrid ESSs for compensation of short-term unbalances of active power in the presence of pulsed loads.

Creating ACS and arranging the operation of hybrid microgrids is more complicated than it is in DC and AC microgrids. A hierarchical ACS of hybrid microgrids, as a rule, has three layers to implement the algorithms of primary, secondary, and tertiary control [174].

Centralized primary control is used in stand-alone hybrid microgrids with PV modules, wind turbines, and DGSs equipped with intelligent power regulators [175]. The regulators implement the maximum power point tracking (MPPT) function. In centralized ACSs, the central microgrid controller provides power balancing by determining the reference voltage and current values for local controllers. The power balancing algorithms are based on the principles of the grid following (the current loop controls the DC bus voltage) and source following (the current loop controls the active power of the grid, and the DC bus voltage is maintained by controlling the DERs). Experiments have confirmed the advantage of the source-following strategy [176]. In both cases, the algorithms of power allocation between DERs fail to take into account the presence of non-linear and unbalanced loads.

Applying the method of coordinated control of a hybrid microgrid with heterogeneous DERs equipped with multi-level power converters allows for taking into account the effect of a non-linear and unbalanced load. The DERs in this case are controlled by a multi-proportional resonant (MPR) controller.

Decentralized primary control of hybrid microgrids is realized by using a droop converter with the *I-U* characteristic for proportional power allocation between DC and AC converters operating in parallel [177]. The current control is implemented in the MPR controller, and the voltage control is implemented in the PI controller. The *I-U* droop coefficient is given by $V_{dc} = V_{dcref} - i_{dc} R_{vd}$, where V_{dc}—DC bus voltage; V_{dcref}—DC bus voltage reference value; i_{dc}—DC bus current, R_{vd}—virtual impedance, which is maintained within the acceptable range according to Equation (11):

$$R_{vd} \leq \frac{\left[\left(V_{dcmax} - V_{dcmrg}\right) - \left(V_{dcmin} + V_{dcmrg}\right)\right]}{I_{dc(fl)}}, \quad (11)$$

where V_{dcmax}—maximum voltage; V_{dcmin}—minimum voltage; V_{dcmrg}—design voltage reserve; $I_{dc(fl)}$—full-load current on the DC side.

This approach does not take into account the AC grid voltage droop control of the hybrid microgrid, which is used in implementing bi-directional power droop control based on normalized and general proportional power allocation [178] (Figure 9).

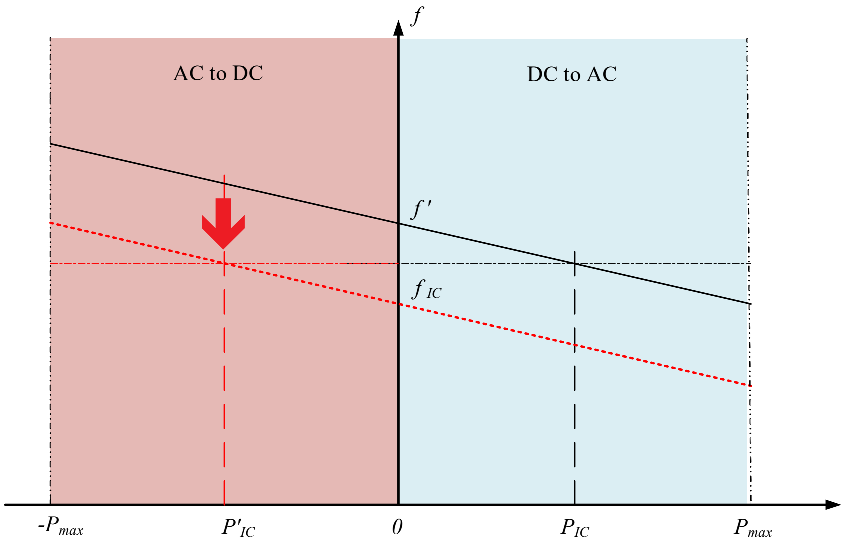

Figure 9. Bi-directional static *P*-*f* control of a hybrid microgrid.

The normalization technique is used to combine the static characteristics of AC and DC grids that use different values. Thus, the normalized frequency in the AC grid and the DC bus voltage are calculated as per Equations (12) and (13).

$$Nf = \frac{f - f^*}{(f_{max} - f_{min})/2}; \quad (12)$$

$$NV_{dc} = \frac{V - V^*_{dc}}{(V_{max} - V_{min})/2}, \quad (13)$$

where Nf and NV_{pu}—normalized values of frequency in the AC grid and DC bus voltage; $f^* = (f_{max} + f_{min})/2$—nominal frequency value; $V^*_{dc} = (V_{max} + V_{min})/2$; f_{max} and f_{min}—maximum and minimum frequency in the AC grid; V_{max} and V_{min}—maximum and minimum voltages in the DC grid.

The two-stage bi-directional droop control method in a hybrid microgrid for optimal power allocation is based on the application of the AC-DC hybrid droop controller [179]. The principle of setting droop in a hybrid microgrid is presented in Figure 10.

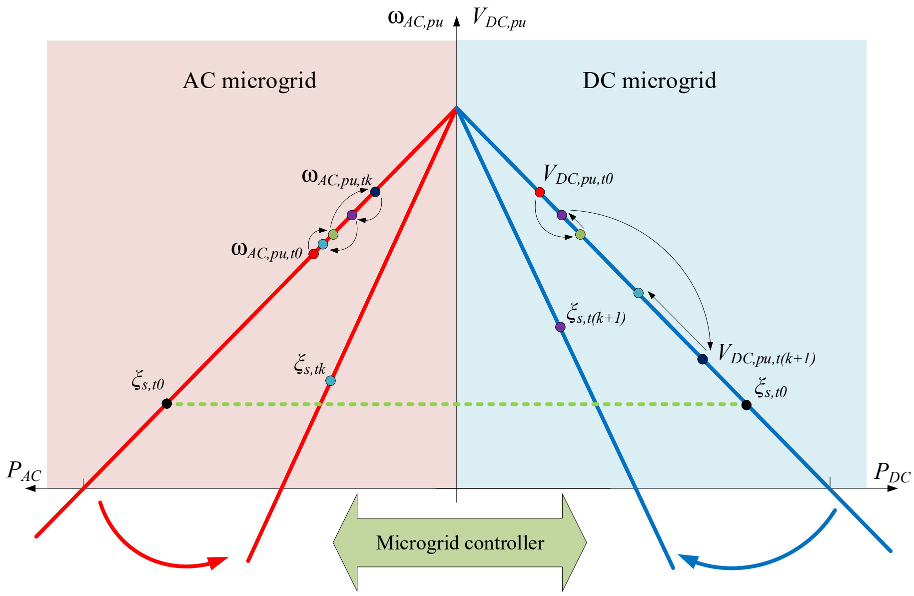

Figure 10. The principle of setting droop in a hybrid microgrid.

The hybrid droop controller uses the V_{dc}-P and ω-P characteristics implemented in the intermediate converter. At the beginning of the operation, the hybrid controller of microgrids gets the initial operating conditions from the AC and DC microgrids (indicated by the black dots in Figure 10). According to the droop control principle, achieving a proportional power allocation between AC and DC microgrids means $\omega_{ac,pu}= V_{dc,pu} = \xi_s$ (the red horizontal line in Figure 10). Thus, as the AC and DC loads in the microgrids change, the value of the active power $P_{MC,\ t_{k+1}}$ to be allocated will update according to the following rule:

$$P_{MC,\ t_{k+1}} = \frac{1}{k_{ac} + k_{dc}} \left(V_{dc,pu,t_{k+1}} - \omega_{ac,pu,t_{k+1}} \right),\ k \geq 0, \tag{14}$$

where k_{ac} and k_{dc}—droop coefficients for AC and DC microgrids, respectively; $V_{dc,pu,t_{k+1}}$—measured DC voltage at time $t = t_{k+1}$; $\omega_{ac,pu,t_{k+1}}$—measured AC frequency at time $t = t_{k+1}$.

Centralized secondary control is implemented through:

- supervisory control based on optimization algorithms;
- coordinated control of DC and AC grids as part of a hybrid microgrid;
- intelligent supervisory control [180].

Supervisory control based on optimization algorithms makes it possible to maximize the use of renewable DERs and minimize the load of DGSs. This takes into account the forecasting error of electricity generation of renewable DERs and its intermittent nature. This extends the battery life of the ESS battery storage by optimizing the charging/discharging processes, as well as reduces the load of the common inverter between the DC and AC grids [181].

Coordinated control allows for efficient control of the hybrid microgrid in both grid-connected and islanded modes of operation. At the same time, the ACS provides MPPT operation of wind turbines and PV modules in the grid-connected mode of microgrid operation [182,183]. In the islanded mode, on-MPPT and off-MPPT modes can be used by wind turbines and PV modules, depending on the control actions of the power control system.

Intelligent supervisory control is implemented by a fuzzy controller that uses a set of rules to control the operation of DC and AC grids as part of a hybrid microgrid [184]. Known practical solutions for EMS implementation make it possible to effectively solve optimization problems aimed at minimizing operating costs in microgrids by means of intelligent charging/discharging control of ESSs [185]. Moreover, the fuzzy controller responds even to small changes in power consumption in hybrid microgrids by adjusting the setpoints for the amount of power output by the fuel-fired DERs.

Decentralized secondary control in hybrid microgrids is effective when distributed ESSs are available, which allows for the implementation of algorithms for local, system-wide, and individual allocation of ESS power [186]. In this case, the central microgrid controller is replaced by a multilevel ACS.

Hierarchical coordinated control is based on the agent-based approach. To this end, the hybrid microgrid is modeled using a differential hybrid Petri net [187,188]. Switching control is implemented at local and system-wide levels with voltage control, including in transients associated with changes in microgrid load flows under emergency disturbances.

Decentralized secondary control in hybrid microgrids can be implemented based on the modified droop for five operating states: ESS charging/discharging, limited ESS charging, limited PV module power, switched off ESSs, and limited power output delivered to the external distribution grid [189,190].

Distributed secondary control can be implemented with communication between PECs of DERs (local controllers) for frequency and voltage regulation in microgrids.

Hierarchical control with a multi-agent structure and consensus-based economic scheduling was proposed and implemented through a case study of a reconfigurable hybrid microgrid.

The agents are:

- energy service company—ensures the safe and reliable operation of the external distribution grid;
- microgrid: responsible for monitoring, economic scheduling, and management of DERs within the microgrid;
- DER: responsible for monitoring, protecting, and implementing primary control functions of each DER [191].

In stand-alone hybrid microgrids, a two-layer multi-agent frequency regulation structure based on an optimized average-consensus algorithm can be implemented in the AC grid. Agents manage both generating DERs and loads. The ACS implements a multi-stage load shedding to restore the frequency in the microgrid when the primary control reserve is exhausted. The advantage of this approach is the efficient exchange of information, as well as quick decision-making when the circuit topology and operating conditions change.

Distributed coordinated control of renewable DERs using subgradients is based on a multi-agent approach. Renewable DERs exchange information with neighboring agents and receive frequency information from the microgrid. Renewable DERs implement bi-level control, with the upper level predicting the amount of active power generation and the lower level controlling the active power. Fuel-fired generating units act as auxiliary sources to regulate the voltage in microgrids, provided that the load profile is served by the output of renewable DERs. When there is a shortage of power from renewable DERs, fuel-fired generating plants serve as the main sources. Frequency measurements are used to set the amount of generation by the fuel-fired generation units, and information about the generation of adjacent DERs is used to obtain information about the amount of the active power reserve [192]. Agent-based control facilitates the reliability of hybrid microgrids through parallel computing. Since communication between agents is prone to security threats, it requires the implementation of measures to ensure information security [193].

Hybrid microgrids have unique features that make them stand apart with respect to the principles of ACS design to be conformed to:

- reliable and efficient management of power flows requires the implementation of a sophisticated control strategy [194];
- they require an additional intermediate converter between the DC and AC grid, which is necessary to maintain the balance of power in the microgrid, both in grid-connected and islanded modes [195];

- the absence of a system-wide variable used for power allocation and frequency and voltage regulation necessitates the use of an ACS with a more elaborate structure and control algorithms [196].

A new trend in the design of modern ACSs of hybrid microgrids is the use of hybrid AC-DC droop, as well as unified frequency and voltage control on both sides (DC and AC grids) [197,198].

5. Experimental Microgrids and Test Systems

Microgrids have a wide geographic range of applications, which is due to innovative research and development of various components for microgrid control systems. To this end, experimental microgrids were built for the specific purpose of determining their design criteria and evaluating the performance of their specifications during operation. The results of research in the field of microgrid testing were reported in [56], where the main recommendations for the design, operation, and integration of microgrids in distribution networks were presented. Microgrid testing can be performed with a demonstration microgrid or a laboratory microgrid emulator. However, laboratory microgrid emulators used for testing, despite the relatively low cost of their design and development, are not very popular [199].

At present, there are two basic concepts for the design of microgrid control systems: the American one, developed by CERTS [53], and the European one, implemented in the MICROGRIDS and MORE MICROGRIDS projects [200]. The key difference between them is that the first concept addresses the issues of heating in addition to the issues of power supply. Other microgrids projects are known to have been implemented around the world:

- NEDO (India [201]): adoption of microgrids at the national level using centralized control systems implemented in the context of poor information and communication infrastructure (TWACS and GPRS communication technologies were used);
- Microgrid UW-Madison [202]: a study of modeling and control problems of microgrids containing generating units connected via PECs in the case of integrating diesel gensets into them;
- DISPOWER, Am Steinweg [203]: a study of the operation of microgrids in a residential complex using a Power Operation and Power Quality Management System (PoMS). The PoMS implements optimization algorithms to control the operation of microgrids, controllers of DERs, and demand response. A key defining feature of the PoMS is a central unit and several decentralized control units;
- Kythnos island microgrid (Greece) [70]: testing of a decentralized approach to microgrid control. An agent-based load controller was used to monitor the state of the island's microgrid by making voltage, current, and frequency measurements. The measurement data were used to coordinate power consumption management in the island's microgrid;
- University of Manchester microgrid/flywheel energy storage laboratory prototype [204]: a study of the joint operation of a synchronous generator and an induction motor coupled together and acting as a single electrical installation, as well as a flywheel storage unit integrated into the microgrid through an inverter. A unique feature of the above topology is the connection of the flywheel storage by means of two inverter units through a line reactance and a coupling transformer. The flywheel storage forms the reference voltage and frequency in the microgrid and provides the necessary fault current for the protection devices to trip.

To maintain the voltage and frequency in experimental and test microgrid circuits, different approaches are used to implement their control systems: centralized control [70,201,204], decentralized control [53,202], and distributed control based on multi-agent systems [200,203]. References [205,206] provided generalized conclusions on the approaches that are deemed preferable in microgrid control systems. Asian countries use centralized control, in contrast to North American countries where decentralized control is employed, and European countries use both centralized and distributed control based on multi-agent systems.

6. Discussion

Microgrid design technology studies are one of the key areas in the expansion planning of power grids, as they make it possible to improve the reliability of power supply to consumers and power quality without significant investment outlays. The highly dispersed integration of diversified DERs poses challenges to the implementation of microgrid control systems.

The availability of different approaches to building microgrid control systems (centralized, decentralized, and distributed) [70] inhibits the formation of a holistic perception of this field, as many contributions try to improve on previously developed solutions, for example, by adding new ways of collecting and processing information. The presence of a hierarchical control system, as the single possible control arrangement [70,98], comes down to a number of variations in its implementation. Therefore, the choice of an approach to the arrangement of microgrid control comes down to the state of the information and communications technology infrastructure. However, when it is poorly developed [201], a centralized approach to microgrid control is implemented. This streamlines the process of interaction with the power system, given that this technology is the most mature at present. If there is no technical possibility to implement centralized control of microgrids, decentralized approaches based on droop control [132,133] and its modifications [134,135,144,145] are applied. A number of studies showed interest in applying algorithms that use virtual impedance [137,138] and virtual inertia [139,140].

Extra difficulties arise when building hybrid microgrids, in which the basic known control algorithms cannot be implemented due to the lack of frequency and certain peculiarities of DC network parameters [172], so one has to rely on two-parameter algorithms [178].

7. Recommendations and Future Research

When choosing an approach to building a microgrid control system, one has to solve a multi-parameter problem, which does not lend itself to the treatment based on conventional criteria (simplicity, convenience, speed). The choice of the microgrid control system should be considered from the standpoint of holonic architectures [103], where each microgrid component is both a stand-alone unit and a part of the microgrid. This principle is well-aligned with the distributed approach to control.

To implement holarchic control [104] on the basis of the distributed approach it is necessary to create digital twins of components and microgrids as a whole. Their use in metaheuristic algorithms will form both predictive and look-ahead controls. The development of quantum computing [207] may allow this concept to be implemented in future research in this field.

8. Conclusions

In the context of large-scale development of DERs, in order to ensure the ability to control power grids of distribution grids, microgrids should be formed so as to mitigate the challenges presented by the intermittent power generation by DERs and consumption by heterogeneous loads.

The optimal choice of structure for microgrids (DC, AC, or AC-DC) reduces power losses and grid modernization costs, ensures efficient frequency and voltage regulation, and maintains power quality parameters within required boundaries, as well as increases the reliability of power supply to consumers.

Microgrids stand apart in that it is impossible to design a standardized ACS structure, which is due to the great variety of DERs, microgrid structures, types of electrical loads, and other factors. Therefore, the ACS structure is formed on a case-by-case basis for each microgrid during its design, taking into account the pros and cons of possible options.

It is possible to ensure the reliable operation of DERs and electrical loads of consumers in the grid-connected and islanded modes of microgrid operation only if the choice of the structure of DERs is optimal.

This article analyzed the state-of-the-art principles of microgrid design that influence the choice of microgrid power flow control methods, as well as power flow control methods themselves. The analysis will prove instrumental in streamlining the process of creating ACSs of microgrids in existing distribution grids of low-voltage AC and AC-DC microgrids.

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Abbreviations

DER	distributed energy resources
RES	renewable energy sources
ESS	energy storage systems
FC	fuel cell
GGS	gas generator sets
DGS	diesel generator sets
ACS	automatic control systems
PCC	point of common coupling
IC	interlinking converter
PEC	power electronic converters
DMS	distribution management system
PI	proportional-integral
PR	proportional-resonance
MPPT	maximum power point tracking
MPR	multi-proportional resonant
VSM	virtual synchronous machine
PoMS	power flow and power quality management system

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