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Trends in Microgrid Control

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***Abstract*—The increasing interest in integrating intermittent renewable energy sources into microgrids presents major challenges from the viewpoints of reliable operation and control. In this paper, the major issues and challenges in microgrid control are discussed, and a review of state-of-the-art control strategies and trends is presented; a general overview of the main control principles (e.g., droop control, model predictive control, multi-agent systems) is also included. The paper classifies microgrid control strategies into three levels: primary, secondary, and tertiary, where primary and secondary levels are associated with the operation of the microgrid itself, and tertiary level pertains to the coordinated operation of the microgrid and the host grid. Each control level is discussed in detail in view of the relevant existing technical literature.**

***Index Terms*—Control, droop control, hierarchical control, microgrid, smart grid.**

LIST OF ACRONYMS:

ACO	Ant Colony Optimization
ADS	Active Distribution System
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
defCERTS	Consortium for Electric Reliability Technology Solutions
CI	Connection Interface
DER	Distributed Energy Resources
DG	Distributed Generation
DNO	Distribution Network Operator
DS	Distributed Storage
DSM	Demand Side Management
DMS	Distribution Management System
ELD	Economic Load Dispatch
EMS	Energy Management System
ESS	Energy Storage System
GA	Genetic Algorithms
GHG	Greenhouse gas
LC	Local Controller
MAS	Multi-agent System
MGCC	Microgrid Central Controller
MPC	Model Predictive Control
defNEDO	New Energy and Industrial Technology Development Organization
OPF	Optimal Power Flow
PC	Point of Connection
PCC	Point of Common Coupling

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PI	Proportional-Integral
PR	Proportional-Resonant
PSO	Particle Swarm Optimization
PV	Photovoltaic
SMES	Superconducting Magnetic Energy Storage
UC	Unit Commitment
VPP	Virtual Power Plant
VSI	Voltage-Source Inverter

I. INTRODUCTION

SMALL autonomic grids have existed for many decades in remote communities where the interconnection with the main power grid is not feasible due to technical and/or economical reasons. Due to their scalability, competitive investment costs and flexible operation, fossil-fuel generation technologies have been the most common choice for supply of electricity in these remote grids. However, with the demonstrated technical and economical feasibility of greener generation technologies based on wind, solar, hydrogen and hydro power, integrating these technologies has become a priority in microgrids.

Policies have been developed to promote green-energy technologies, including feed-in tariffs, renewable portfolio standards, tradable green certificates, investment tax credits and capital subsidies, among others. In Europe, the UK is aiming for 15% of its electricity to be generated from renewable energy sources by 2015/16, which represents an increase of around 10% compared to the existing share; Germany, with a more aggressive policy, targets a 25–30% share by 2020, and 50% by 2030 [1]. According to the trends observed in 2009 for the EU, nearly 55% of the new installed capacity based on renewable sources corresponds to wind and solar-Photovoltaic (PV) intermittent generation (39% and 16%, respectively) [1]. In the US, the state of California has set a target of 33% for the retail load to be served from renewable sources by 2020 [2], [3]. In Canada, the province of Ontario has an aggressive policy for the promotion of energy conservation and investments in renewable energy sources, as part of an overall climate change action plan; according to the Ontario Green Energy Act (2009) [4], renewable energy sources are granted long-term contracts with predefined feed-in tariffs in order to reduce the risk for investors, and progressively phase out the existing coal-fired generators.

In order to successfully integrate renewable Distributed Energy Resources (DER), many technical challenges must yet be overcome to ensure that the present levels of reliability are not significantly affected, and the potential benefits of distributed generation are fully harnessed. In this sense, the main issues include [5], [6]:

- Schedule and dispatch of units under supply and demand uncertainty, and determination of appropriate levels of reserves.
- Reliable and economical operation of microgrids with high penetration levels of intermittent generation in stand-alone mode of operation.
- Design of appropriate Demand Side Management (DSM) schemes to allow customers to react to the grid's needs.
- Design of new market models that allow competitive participation of intermittent energy sources, and provide appropriate incentives for investment.
- Reengineering of the protection schemes at the distribution level to account for bidirectional power flows.
- Development of new voltage and frequency control techniques to account for the increase in power-electronics-interfaced distributed generation.
- Develop market and control mechanisms that exhibit a plug-and-play feature to allow for seamless integration over time.

The microgrid concept [7] is a quite appealing alternative for overcoming the challenges of integrating DER units, including renewable energy sources, into power systems. However, in order to allow seamless deployment of microgrids, several issues still remain unsolved. Currently, effort is being put into the design of special protection schemes and control systems that ensure reliable, secure and economical operation of microgrids in either grid-connected or stand-alone mode. This paper presents a general overview of the existing technologies and remaining challenges in microgrid control.

The rest of the paper is organized as follows: Section II discusses the concept of microgrid and its various evolved forms. Section III reviews the requirements of microgrid control and protection systems, and discusses its most relevant challenges. Section IV presents an overview of hierarchical control systems applied to microgrids and discusses the classification of control features in different hierarchical levels. Sections V and VI review the state-of-the-art in microgrid's primary and secondary control levels, respectively. Finally, some conclusions are drawn in Section VII.

II. MICROGRID DEFINITIONS

The concept of microgrid was first introduced in the technical literature in [8] and [9] as a solution for the reliable integration of DERs, including Energy Storage Systems (ESSs) and controllable loads. Such microgrid would be perceived by the main grid as a single element responding to appropriate control signals. Although a detailed definition of microgrids is still under discussion in technical forums, a microgrid can be described as a cluster of loads, Distributed Generation (DG) units and ESSs operated in coordination to reliably supply electricity, connected to the host power system at the distribution level at a single point of connection, the Point of Common Coupling (PCC). The adoption of microgrids as the paradigm for the massive integration of distributed generation will allow technical problems to be solved in a decentralized fashion, reducing the need for an extremely ramified and complex central coordination and facilitating the realization of the Smart Grid.

In general, a microgrid can have any arbitrary configuration, as illustrated in Fig. 1; however, some entities, such as the Consortium for Electric Reliability Technology Solutions (CERTS), promote a configuration in which loads are connected to the feeders with existing generation [10]. In some cases, where a strong coupling between the operation of different energy carrier systems (heating, hot water, etc.) exists, microgrids can integrate and operate all these energy carriers in coordination.

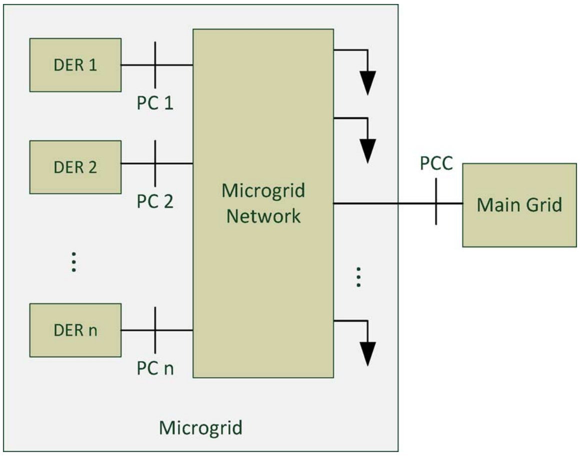


Fig. 1. Schematic diagram of a generic multiple-DER microgrid.

Different initiatives around the world aim to further develop the concept of microgrid through research, development, and demonstration (RD&D). These projects include those of Bella Coola [11] and Hydro-Quebec in Canada, CERTS in the United States, Microgrids and More Microgrids in Europe, Huatacondo in Chile [12], and New Energy and Industrial Technology Development Organization (NEDO) in Japan [7].

A Microgrid and its various evolved forms, such as Active Distribution System (ADS), cognitive microgrid, and Virtual Power Plant (VPP) [13]–[17], can be considered and exploited as a main building block of the Smart Grid. An ADS is a microgrid equipped with power management and supervisory control for DG units, ESSs and loads [18]. A cognitive microgrid is an intelligent microgrid that features an adaptive approach for the control of the microgrid components. Thus, in the context of VPP [15], the cognitive microgrid is presented to the host grid at the PCC as a single market agent with a prespecified performance; the internal mechanisms and composition of the VPP are hidden from the host power system. It is important to note that the VPP is not limited to a microgrid scope; in fact, the coordination of multiple DG units throughout a bulk power system is also considered as a VPP solution.

A microgrid is capable of operating in grid-connected and stand-alone modes, and handling the transitions between these two modes [19], [20]. In the grid-connected mode, the power deficit can be supplied by the main grid and excess power generated in the microgrid can be traded with the main grid and can provide ancillary services. In the islanded mode of operation, the real and reactive power generated within the microgrid, including the temporary power transfer from/to storage units, should be in balance with the demand of local loads. IEEE Standard 1547 includes guidelines for interconnection of DER units [21]. Islanding, i.e., disconnection of the microgrid from the host grid, can be either intentional (scheduled) or unintentional. Intentional islanding can occur in situations such as scheduled maintenance, or when degraded power quality of the host grid can endanger microgrid operation. Unintentional islanding can occur due to faults and other unscheduled events that are unknown to the microgrid; proper detection of such a disconnection is imperative for safety of personnel, proper operation of the microgrid, and implementation of changes required in the control strategy. The technical literature offers a wealth of islanding detection algorithms, which operate based on frequency/voltage measurements (pasive) or disturbance injection (active) (e.g., [22], [23]).

Microgrids that do not have a PCC are called *isolated microgrids*. This is the case of remote sites (e.g., remote communities or remote industrial sites) where an interconnection with the main grid is not feasible due to either technical and/or economic constraints; therefore, isolated microgrids operate permanently in stand-alone mode.

III. CONTROL AND PROTECTION REQUIREMENTS

Microgrids, and integration of DER units in general, introduce a number of operational challenges that need to be addressed in the design of control and protection systems in order to ensure that the present levels of reliability are not significantly affected and the potential benefits of DG are fully harnessed. Some of these challenges arise from invalid assumptions typically applied to conventional distribution systems, while others are the result of stability issues formerly observed only at a transmission system level.

The most relevant challenges in microgrid protection and control include:

- *Bidirectional power flows*: While distribution feeders were initially designed for unidirectional power flow, integration of DG units at low voltage levels can cause reverse power flows and lead to complications in protection coordination, undesirable power flow patterns, fault current distribution, and voltage control.
- *Stability issues*: Local oscillations may emerge from the interaction of the control systems of DG units, requiring a thorough small-disturbance stability analysis. Moreover, transient stability analyses are required to ensure seamless transition between the grid-connected and stand-alone modes of operation in a microgrid.
- *Modeling*: Prevalence of three-phase balanced conditions, primarily inductive transmission lines, and constant-power loads are typically valid assumptions when modeling conventional power systems at a transmission level; however, these do not necessarily hold valid for microgrids, and consequently models need to be revised.
- *Low inertia*: Unlike bulk power systems where high number of synchronous generators ensures a relatively large inertia, microgrids might show a low-inertia characteristic, especially if there is a significant share of power electronic-interfaced DG units. Although such an interface can enhance the system dynamic performance, the low inertia in the system can lead to severe frequency deviations in stand-alone operation if a proper control mechanism is not implemented.
- *Uncertainty*: The economical and reliable operation of microgrids requires a certain level of coordination among different DERs. This coordination becomes more challenging in isolated microgrids, where the critical demand-supply balance and typically higher component failure rates require solving a strongly coupled problem over an extended

horizon, taking into account the uncertainty of parameters such as load profile and weather forecast. This uncertainty is higher than those in bulk power systems, due to the reduced number of loads and highly correlated variations of available energy resources (limited averaging effect).

The microgrid's control system must be able to ensure the reliable and economical operation of the microgrid, while overcoming the aforementioned challenges. In particular, desirable features of the control system include:

- *Output control*: Output voltages and currents of the various {DER} units must track their reference values and ensure oscillations are properly damped.
- *Power balance*: DER units in the microgrid must be able to accommodate sudden active power imbalances, either excess or shortage, keeping frequency and voltage deviations within acceptable ranges.
- *DSM*: Where applicable, proper DSM mechanisms must be designed in order to incorporate the ability to control a portion of the load. Additionally, for the electrification of remote communities with abundant local renewable resources, the active participation of the local community may be beneficial in order to design cost-effective DSM strategies that enhance load-frequency control [24], [25].
- *Economic dispatch*: An appropriate dispatch of DER units participating in the operation of a microgrid can significantly reduce the operating costs, or increase the profit. Reliability considerations must also be taken into account in the dispatch of units, especially in stand-alone operation.
- *Transition between modes of operation*: A desirable feature of microgrids is the ability to work in both grid-connected and stand-alone modes of operation, including a smooth transition between them. Different control strategies might be defined for each mode of operation and, therefore, a high-speed islanding detection algorithm is very important in order to adjust the control strategy accordingly [26].

In the microgrid environment, characterized by having frequent and multiple changes in topology, robustness and adaptiveness of controllers are desired traits. Availability of measurements, communication, and high-speed computational facilities are additional challenges for all the above requirements; for this reason, an attempt should be made in order to reduce the need for high-speed communications and computation in critical tasks. The adoption of a hierarchical control structure is quite appealing given the different time constants involved, including fast dynamics in the output controls and slower dynamics in the economic dispatch. Complexity and sophistication of the solutions for the control requirements of the microgrid will be very much dependent on whether it is designed to primarily operate in stand-alone or grid-connected mode. While in grid-connected mode of operation emphasis is put on the interaction with the main grid, reliability issues are more significant in stand-alone mode of operation. A description of controlled variables used in microgrid control and different types of DER units is presented next.

A. Controlled Variables

The main variables used to control the operation of a microgrid are voltage, frequency, and active and reactive power. In the grid-connected mode of operation, the frequency of the microgrid and the voltage at the PCC are dominantly determined by the host grid. The main role of the microgrid control in this case is to accommodate the active and reactive power generated by the DER units, and the load demand. Reactive power injection by a DER unit can be used for power factor correction, reactive power supply, or voltage control at the corresponding Point of Connection (PC). In this mode, the host utility may not allow regulation or control of the voltage by DER units in proximity of the PCC (determined by the electrical distance and Short Circuit MVA of the grid) to avoid interaction with the same functionality provided by the grid [21].

In stand-alone mode of operation, the microgrid operates as an independent entity. This mode of operation is significantly more challenging than the grid connected mode, because the critical demand-supply equilibrium requires the implementation of accurate load sharing mechanisms to balance sudden active power mismatches. Voltages and frequency of the microgrid are no longer supported by a host grid, and thus they must be controlled by different DER units. Power balance is ensured either directly by local controllers utilizing local measurements, or by a central controller that communicates appropriate set points to local controllers of different DER units and controllable loads. The main objective of such a mechanism is to ensure that all units contribute to supplying the load in a pre-specified manner. A minute mismatch in the amplitude, phase angle or frequency of the output voltage of any unit in the group can lead to a relatively high circulating current. This problem is extensively investigated in the literature and different control schemes are proposed to overcome the issue [27]–[31]. One possible approach is to have one inverter operate as a master unit that regulates the voltage of the microgrid [32]. The same unit can also control the frequency in open loop through an internal crystal oscillator. This DER unit can be operated similar to a synchronous generator with a reactive power-voltage droop characteristic, while the remaining DER units inject active and reactive power according to the set points determined by the secondary controller [33].

A similar strategy can also be applied to the control of DC microgrids, where a master DER unit can be assigned to control the voltage level of the microgrid, compensating for instantaneous active power mismatches. Alternatively, several units can share active power mismatches using active power-voltage droop characteristics [34].

B. Types of DER Units

The DER units present in a particular microgrid are very problem-specific and depend on a variety of factors, including whether the microgrid is designed to operate in grid-connected or stand-alone mode, the different generation technologies deployed, and the topology of the system [35]. In general, the components that can be found in a purely-electrical microgrid are illustrated in Fig. 2.

Microgrids are characterized by a single point of connection with the host grid. The Connection Interface (CI) at the PCC can be realized using electro-mechanical circuit breakers, solid state switches or even back-to-back converters. The connection of DC-type energy sources such as PV panels, fuel cells and energy

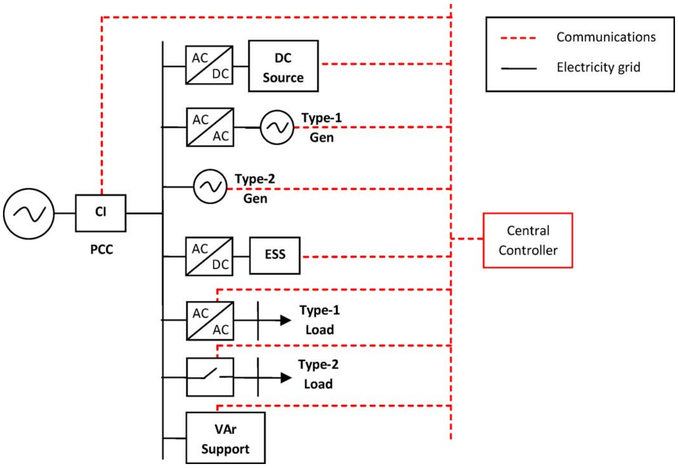


Fig. 2. Microgrid general components.

storage technologies (batteries and ultracapacitors) requires the use of a DC-to-AC power converter interface. While some conventional generators can be connected directly to the microgrid and operate at 50/60 Hz, variable-speed generators such as wind turbines using synchronous machines, and high-speed microturbines require the use of AC-to-AC power converters to match the constant frequency and voltage of the microgrid. Wind turbines can also operate with low flexibility using induction generators directly connected to the system, or use the more flexible doubly-fed induction generator. Loads within the microgrid can be controlled using either a conventional circuit breaker or a more sophisticated AC-to-AC power electronic interface to allow more flexible control. Reactive power support can be provided by capacitor banks, SVCs or STATCOMs.

DER units can also be categorized based on their dispatchability. Dispatchable units (e.g., diesel generators) can be fully controlled; however, nondispatchable units cannot, and are typically operated to extract the maximum possible power. DER units based on renewable energy sources (e.g., a wind turbine or photovoltaic units) are generally intermittent and their output is not controllable.

C. Energy Storage Systems

Integrated storage can decrease losses and increase reliability. Energy storage enables large-scale integration of intermittent renewable energy sources [36]. The benefits of storage in the latter application are of particular interest, because while renewable energy resources are a pillar of the microgrids, without storage, their generation cannot improve the system reliability and has to be duplicated by other means of generation. A storage unit can provide a functionality similar to that of the inertia of a synchronous generator by absorbing temporary mismatches between power generation and demand, especially in a low inertia power electronic-based microgrid. Therefore, system stabilization can be improved by providing voltage/frequency control in a droop-based scheme.

Despite its benefits, energy storage has not been fully utilized. Among the limiting factors is, besides the cost, the lack of appropriate control and management strategies [37]. Future research is needed to investigate and develop control methodologies for the following different energy storage technologies, with different energy and power ratings and efficiencies and in different applications (e.g., diurnal renewable resources levelizing, reserve augmentation, voltage support, and reliability enhancement) [38]–[42]: Battery Energy Storage System (BESS), Compressed Air Energy Storage (CAES) systems, flywheels, thermal energy storage, pumped hydro, Superconducting Magnetic Energy Storage (SMES) and vehicle-to-grid (V2G) technologies [43].

Energy storage has applications in transmission capability improvement, power quality enhancement, microgrid islanded operation, active distribution systems, and electric vehicle technologies, and may improve dynamic stability, transient stability, voltage support, and frequency regulation [40], [44], [45]. The power grid can substantially benefit from the availability of stored energy in generation, transmission, distribution, and consumption [46]. For example, storage can eliminate or delay expansion of the transmission infrastructure or generation capacity. Storage can be combined with nondispatchable DER units such as wind and solar energy to turn them into dispatchable units. On the consumers' side, storage can be employed for peak-shaving by storing the locally generated energy until it is needed. An extensive list of applications for energy storage in transmission, distribution, and generation is presented in [47].

IV. CONTROL HIERARCHY IN A MICROGRID

With regard to the architecture of a power system's control, two very distinctive opposite approaches can be identified: centralized and decentralized. A fully centralized control relies on the data gathered in a dedicated central controller that performs the required calculations and determines the control actions for all the units at a single point, requiring extensive communication between the central controller and controlled units. On the other hand, in a fully decentralized control each unit is controlled by its local controller, which only receives local information and is neither fully aware of system-wide variables nor other controllers' actions [48], [49].

Interconnected power systems usually cover extended geographic areas, making the implementation of a fully centralized approach infeasible due to the extensive communication and computation needs. At the same time, a fully decentralized approach is also not possible due to the strong coupling between the operations of various units in the system, requiring a minimum level of coordination that cannot be achieved by using only local variables. A compromise between fully centralized and fully decentralized control schemes can be achieved by means of a hierarchical control scheme consisting of three control levels: primary, secondary, and tertiary. These control levels differ in their (i) speed of response and the time frame in which they operate, and (ii) infrastructure requirements (e.g., communication requirements). Although microgrids are not necessarily as geographically expansive as conventional power systems, they can benefit from this control hierarchy, depicted in Fig. 3, because of the large number of controllable resources and stringent performance requirements [50]–[53].

The rest of this section presents an overview of different control levels from the perspective of microgrids. Subsequent sections present the state of the art in control methods pertaining to different levels.

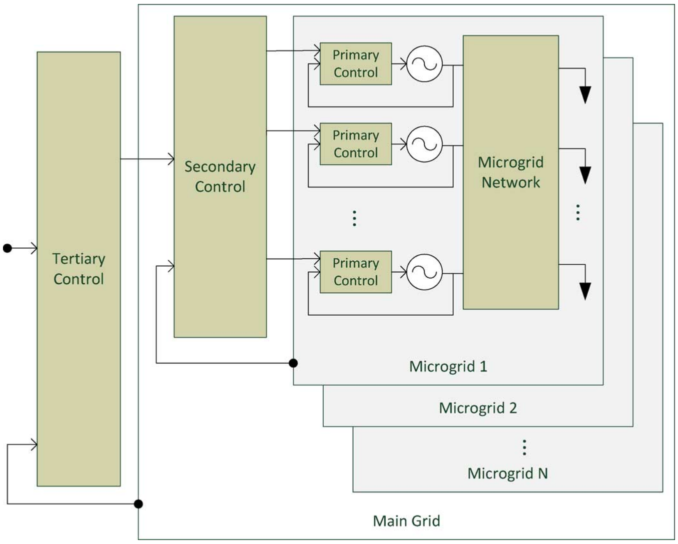


Fig. 3. Hierarchical control levels: primary control, secondary control, and tertiary control.

A. Primary Control

Primary control, also known as local control or internal control, is the first level in the control hierarchy, featuring the fastest response. This control is based exclusively on local measurements and requires no communication. Given their speed requirements and reliance on local measurements, islanding detection, output control and power sharing (and balance) control are included in this category [19], [20], [22]. In synchronous generators, output control and power sharing is performed by the voltage regulator, governor, and the inertia of the machine itself.

Voltage-Source Inverters (VSIs) used as interface for DC sources, or as part of back-to-back converters, require a specially designed control to simulate the inertia characteristic of synchronous generators and provide appropriate frequency regulation. For this purpose, VSI controllers are composed of two stages: DG power sharing controller and inverter output controller. Power sharing controllers are responsible for the adequate share of active and reactive power mismatches in the microgrid, whereas inverter output controllers should control and regulate the output voltages and currents [19], [20], [32], [54], [55]. Inverter output control typically consists of an outer loop for voltage control and an inner loop for current regulation. Power sharing is performed without need for communication by using active power-frequency and reactive power-voltage droop controllers that emulate the droop characteristics of synchronous generators [56].

B. Secondary Control

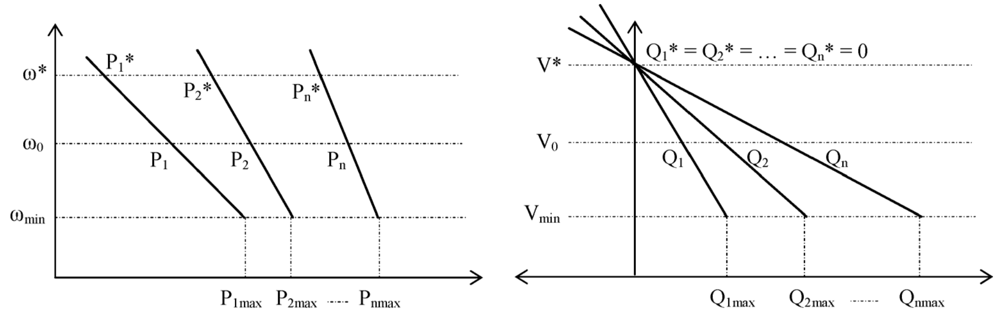
Secondary control, also referred to as the microgrid Energy Management System (EMS), is responsible for the reliable, secure and economical operation of microgrids in either grid-connected or stand-alone mode. This task becomes particularly challenging in isolated microgrids with the presence of highly-variable energy sources, where the update rate of the unit dispatch command should be high enough to follow the sudden changes of load and non-dispatchable generators. The objective of the EMS consists of finding the optimal (or near optimal) Unit Commitment (UC) and dispatch of the available DER units, so that certain selected objectives are achieved. Permanent voltage and frequency deviations produced by the action of the primary control are also restored by the secondary control. In order to determine the dispatch and UC of the microgrid, three main options are identified: real-time optimization, expert systems, and decentralized hierarchical control [57].

For the EMS architecture, two main approaches can be identified: centralized and decentralized architectures. Secondary control is the highest hierarchical level in microgrids operating in stand-alone mode, and operates on a slower time frame as compared to the primary control in order to (i) decouple secondary control from primary control [58], (ii) reduce the communication bandwidth by using sampled measurements of the microgrid variables, and (iii) allow enough time to perform complex calculations. The typically limited geographical span of microgrids facilitates communication through affordable and simple standard protocols [59], which needs to be of low bandwidth and only for slowly changing parameters, such as set points for real and reactive power [60]. According to the Galvin electricity initiative [61], a central controller is required to ensure that the power system operation is as seamless as possible during major disturbances such as transition from grid-connected mode to islanded mode. In the proposed approach, the master controller is responsible for economic optimization of the microgrid whenever possible (i.e., in non-emergency mode of operation and when connected to the main grid), as well as maintaining reliable, secure, and safe operation of the grid. In [62], optimal operation is sought through the implementation of a market environment using a Multi-agent System (MAS), where the individual DER units are controlled by local agents that exchange information with a central controller to determine their buying and selling bids.

C. Tertiary Control

Tertiary control is the highest level of control and sets long term and typically "optimal" set points depending on the requirements of the host power system. This tertiary control is responsible for coordinating the operation of multiple microgrids interacting with one another in the system, and communicating needs or requirements from the host grid (voltage support, frequency regulation, etc.). For example, the overall reactive power management of a grid that contains several microgrids could be accomplished by properly coordinating, through a tertiary control approach, the reactive power injection of generators and microgrids at the PCC, based on a centralized loss minimization approach for the entire grid. This control level typically operates in the order of several of minutes, providing signals to secondary level controls at microgrids and other subsystems that form the full grid. Secondary controls, on the other hand, coordinate internal primary controls within the microgrids and subsystems in the span of a few minutes. Finally, primary controls are designed to operate independently and react in predefined ways instantaneously to local events.

Tertiary control can be considered part of the host grid, and not the microgrid itself. Hence, this control level is not discussed further in this paper.



(a) (b)

Fig. 4. Conventional droop characteristics. (a) P-ω droop. (b) Q-V droop.

A key issue that impacts the secondary and tertiary control in the case of isolated microgrids is the community involvement [12], [25]. The design of appropriate DSM schemes that allow the community to respond to microgrid needs can be achieved through an extension of conventional SCADA approaches [25], [63]. Also, supervision and maintenance activities carried out by the community will have an impact on input parameters of secondary and tertiary controls [63].

V. PRIMARY CONTROL STATE-OF-THE-ART

A. Inverter Output Control

Control of electronically coupled DER units in microgrids has been discussed extensively in the technical literature. A general overview of grid-side converter controllers is given in [54], [64], in which controllers are categorized based on their reference frame: synchronous (dq), stationary ($\alpha\beta$), and natural (abc). The synchronous reference frame is associated with dc variables and PI-based controllers. The stationary reference frame is associated with sinusoidal variables and Proportional-Resonant (PR) controllers. The natural reference frame utilizes controllers realized in the form of Proportional-Integral (PI), PR, hysteresis, or dead-beat [54].

The inverter output control typically consists of an outer loop for voltage control, and an inner loop for current regulation. A common approach to the design of the control loops is the use of PI controllers, with additional feed-forward compensation to improve the performance of current regulators [54], [65], [66]. A comprehensive review of inverter output control strategies and their main characteristics is presented in [67].

Multivariable control methods have been proposed in [68], [69] to improve the dynamic response of microgrids and ensure robust stability against uncertainties in load parameters due to presence of nonlinear loads. Research on multivariable control of microgrids has primarily focused on the voltage regulation of a single-DG-unit microgrid with its dedicated RLC load, where load parameters are perturbed around their nominal rated values [68] or within a pre-specified range [69].

Although extensive research has been carried out on the development of microgrid primary control strategies, the following areas can benefit from further research: improving robustness to topological and parametric uncertainties; improving transient response of the controllers; obviating the need for complex communication infrastructure; accounting for imbalance and harmonics; enhancing scalability of the control schemes; incorporating the dc-side dynamics in the control design; improving fault ride-through capabilities; and developing control schemes that function for both grid-tied and islanded modes of operation of the microgrid and provide a smooth transition.

B. Power Sharing Control

A second stage within the primary control of microgrids is the power sharing control. This control can be categorized based on whether or not they employ the concept of droop. Power sharing control using a central controller can also be considered as part of the secondary control [70].

1) Droop-Based Methods: Controlling DER units based on droop characteristics is ubiquitous in the literature [20], [55], [56], [71]–[75]. Droop methods originate from the principle of power balance of synchronous generators in large interconnected power systems. An imbalance between the input mechanical power of the generator and its output electric active power causes a change in the rotor speed which is translated into a deviation in frequency. Similarly, output reactive power variation results in deviation in voltage magnitude. The frequency-power droop control method is inherent to the steady-state operation of conventional DG units such as synchronous generators, and it can be artificially crafted for electronically interfaced DG units.

In droop control, the relationship between real power/frequency and reactive power/voltage can be expressed as:

$$\begin{aligned} \omega_o &= \omega^* - K_P(P_o - P^*) \\ V_o &= V^* - K_Q(Q_o - Q^*) \end{aligned} \tag{1}$$

where the values ω^* and V^* correspond to the reference values for angular frequency and voltage, respectively, and ω_o and V_o correspond to the measured output frequency and voltage of the DG system, respectively. A similar convention is used for the active power P and reactive power Q. The coeficients K_P and K_Q denote droop coefficients, and are determined based on steady-state performance criteria [56], [72], [76].

A conventional P-ω droop characteristic is shown in Fig. 4(a), while a basic Q-V droop characteristic is shown in Fig. 4(b). For illustration purposes, it is assumed that at nominal voltage conditions, DG units do not supply reactive power to the grid, thus providing active power at unity power factor in this case. In Fig. 4(a), $\omega_{\min}$ and $V_{\min}$ correspond to the minimum acceptable frequency and output voltage, respectively.

A different approach is proposed in [77]–[79], where the active power is controlled using the output voltage and the reactive power is controlled using the output frequency, which is exactly the opposite of typical controls in conventional synchronous generators. The proposed control is based on a dynamic model of the interfacing VSI that shows dependency between reactive power and frequency, and between active power and output voltage; however, this control scheme may not be suitable for microgrids with a mix of power electronic-interfaced and directly connected DG units.

The main advantage of droop control is that it eliminates the need for communication and the control action is merely based on local measurements. This feature gives droop control significant flexibility in that, as long as the balance between generation and demand can be maintained, there is no interdependency of the local controllers, i.e., the controller performs its task based on local measurements and droop characteristics accordingly. However, the conventional droop control method has several disadvantages [50], [78], [80], [81]:

- Poor transient performance or instability issues due to the use of average values of active and reactive power over a cycle.
- Ignoring load dynamics that can result in failure subsequent to a large or fast load change.
- Inability for black-start-up after system collapse, requiring special provisions for system restoration.
- Poor performance when adopted for distribution networks due to their low X/R ratio, which increases the coupling of active and reactive power.
- Inability to provide accurate power sharing among the DER units due to output impedance uncertainties.
- Unsuitability for nonlinear loads since it does not account for harmonic currents.
- Inability to impose a fixed system frequency independent of system loading conditions.

A particularly interesting result is reported in [65], where an eigenvalue analysis of a linearized microgrid model shows that slower oscillatory modes (close to the real axis), associated with the droop controllers loops, present important variations with changes on the operating conditions of the system. Furthermore, damping factors of the aforementioned slower modes migrate to lower values when the active power output of the DG unit is increased [65], [82]. Modified droop control methods have been proposed to overcome these drawbacks. A frequency restoration loop is proposed in [76] to maintain the system frequency at the nominal value. Reference [83] introduces a virtual output resistance to achieve automatic harmonic power sharing and reduced oscillations. To overcome the issues of power sharing inaccuracy and active/reactive power coupling in distribution networks, the control loop is augmented with a virtual inductive output impedance in [79], [84], [85]. Reference [71] transforms the actual P and Q variables into virtual P' and Q' variables to achieve decoupling between real and reactive power for a microgrid with a low X/R ratio. However, since in this method virtual power is being directly controlled, power sharing between different DG units is compromised. Reference [86] achieves better decoupling and power sharing by alternatively performing the orthogonal transformation from the actual V-ω frame to a virtual V'-ω' frame. Overviews of some of the aforementioned strategies are presented in [67], [70]. In [67], different schemes are adopted for grid-feeding, grid-supporting and grid-forming inverters.

An adaptive droop function is employed in [65] to preserve the stability of the system for different loading conditions. An adaptive feedforward compensation mechanism is proposed in [81] to improve the stability of the microgrid at different operating points. A hierarchical control scheme is proposed in [50] to improve the flexibility and expansibility of droop-based microgrids. This control scheme includes a primary droop controller, a secondary control loop to restore voltage and frequency to the original values after system changes, and a tertiary control to regulate the power flow between the microgrid and the external grid. To achieve a robust performance, in [66], inverter controllers are designed based on L_1-robust control, and droop coefficients are optimized using Particle Swarm Optimization (PSO). To account for fluctuations in the dc link voltage, [87] adds a $V_{\mathrm{dc}}/V_{\mathrm{ac}}$ droop characteristics to the conventional droop control method and thereby achieves a constant output power despite dc link voltage variations. Drooping the inverter voltage angle rather than its frequency is proposed in [88] to achieve a better transient performance; however, a synchronized signal is required in this method for phasor measurement. The problem of controlling microgrids that include unbalanced and nonlinear loads is addressed in [89]–[92], where power sharing is achieved based on droop control, and harmonic/imbalance rejection is performed by the primary controller. Small signal stability and eigenvalue analysis of converter-fed microgrids that are controlled based on droop characteristics have also been reported in the literature [82], [85], [93], [94], concluding that the dominant modes of the closed loop system are determined by droop controllers, and the overall stability of the system mainly depends on droop control gains, system loading conditions, and network parameters.

Power management is an important challenge to be addressed by controls of a microgrid. One active power management strategy (P-ω droop) and three reactive power management strategies (V-Q droop, voltage regulation, and power factor correction) are proposed in [76], [95]. These papers, however, do not present the decision making process regarding the selection among these strategies, which should consider the overall performance of the microgrid, characterized by generation economics, market structure and microgrid stability.

Some additional considerations to the design of the power sharing control can arise when the different types of DER systems and configurations are included in the analysis. Depending on the amount of energy available in storage devices and the particular time constants of each energy source, the share of the microgrid power mismatch among the different units may need to be different for different time scales. The study of more sophisticated droop functions including more advanced control techniques ranging from more complex transfer functions to fuzzy controllers, Artificial Neural Networks (ANNs) and other heuristic approaches is an active area of research.

2) Non-Droop-Based Methods: The following control methods address primary control in a multi-DER microgrid from a centralized perspective:

- A centralized controller is proposed in [93], [96], where the total load current is measured and transmitted to a central controller. Then, based on each DER unit characteristics, the contribution of each unit is determined and output current reference set points are sent back to the units; an outer loop simultaneously controls the voltage of the system. This method results in fast mitigation of transients; however, communication is crucial and its failure will lead to system collapse.
- Reference [32] proposes a master-slave control strategy, in which a dominant DG unit undertakes the task of maintaining system voltage within a permissible range and other units supply the load. This method is inspired on the conventional power system operational concept in which a slack bus controls voltage and frequency, and a number of PQ-buses either inject or absorb active and reactive power. As long as a balance between the load and generation is maintained, this method is flexible with respect to connection and disconnection of DER units. However, the presence of the dominant DG unit is crucial.
- A method for voltage control and power sharing among multiple parallel DER units in a microgrid is proposed in [60]. This method uses a low-bandwidth communication link to achieve power sharing and voltage control through a central controller. Local controllers are responsible for harmonic and imbalance rejection.
- A voltage control and power sharing scheme is proposed in [97] in which one DG unit controls the PCC voltage using a nested control loop and others are controlled in current control mode. Equal current sharing and synchronization is achieved using a CANbus communication link.

VI. SECONDARY CONTROL STATE-OF-THE-ART

Secondary control is responsible for the economical and reliable operation of the microgrid, and this functionality is also referred to as the microgrid EMS. Two main approaches can be identified in this area: centralized and decentralized. While the centralized approach relies on the operation of a central controller, the decentralized approach allows the interaction of the various units within the microgrid in order to facilitate a distributed decision making process.

The adoption of a centralized approach enables the implementation of online optimization routines, given that all the relevant information is gathered at a single point, at the same time; however, it does not exhibit the desirable plug-and-play feature. On the other hand, the decentralized approach can easily incorporate new DER units without need to make continuous changes to the controller settings, but it has difficulties handling operation of microgrids requiring high levels of coordination. In general, centralized approaches are more suitable for isolated microgrids with critical demand-supply balances and a fixed infrastructure, while decentralized approaches are more suitable for grid-connected microgrids, with multiple owners and fast-changing number of DER units. A detailed description of the centralized and decentralized approaches is presented next.

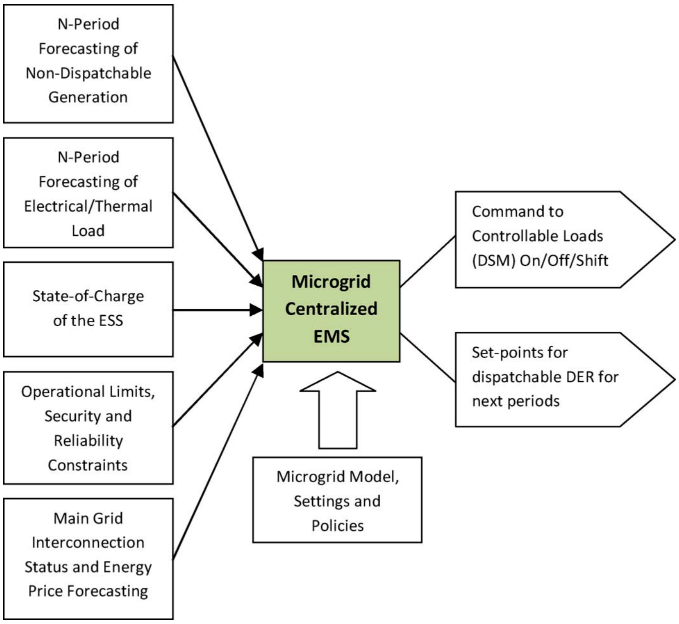


Fig. 5. Centralized approach to secondary control of microgrids.

A. Centralized Approach

A centralized secondary control architecture consists of a central controller provided with the relevant information of every DER unit and load within the microgrid, and the network itself (e.g., cost functions, technical characteristics/limitations, network parameters and modes of operation), as well as the information from forecasting systems (e.g., local load, wind speed, solar irradiance) in order to determine an appropriate UC and dispatch of the resources according to the selected objectives. The central controller can make decisions using either online calculations of the optimal (or near optimal) operation, or pre-built and continuously-updated databases with information of suitable operating conditions, from offline calculations or other heuristic approaches. A practical application of this approach is demonstrated in [11].

The general structure of a centralized secondary control for microgrids is shown in Fig. 5, where the input variables/parameters may include:

- Forecasted power output of the non-dispatchable generators for the following N consecutive periods.
- Forecasted local load for the following N consecutive periods.
- State of charge of the ESS.
- Operational limits of dispatchable generators and ESS.
- Security and reliability constraints of the microgrid.
- Utility grid interconnection status.
- Forecasting of the grid energy prices.

Output variables of the secondary controller are the reference values of the primary control system (e.g., output power and/or terminal voltage) for each dispatchable DER unit, together with decision variables for controlling loads for load shifting or shedding.

1) Optimal Dispatch: In small microgrids with a low number of generation scenarios, the offline calculation of the optimal operation for all the possible scenarios may be the best alternative in terms of cost and system's performance. In the approach presented in [2], all possible operation states are analysed offline and the optimal dispatch of the system for each scenario is calculated and stored in a look-up table to be accessed in real-time operation. Although this approach produces an instantaneous response of the system when the conditions change, the number of possible scenarios can become an issue if distribution system faults are considered, or if thermal loads are to be optimized jointly with the electrical loads. Furthermore, the presence of ESS in the microgrid introduces time dependence in the calculation of the optimal dispatch; therefore, the optimal dispatch is not solely determined by a particular demand scenario. A similar approach is presented in [98], where a feed-forward ANN with one hidden layer is trained with results of the Optimal Power Flow (OPF) for several feasible scenarios of the microgrid. However, the use of significant ESS capacity is not considered in this case, and its optimal management would require a multistage OPF calculation, which will greatly increase the number of scenarios to be considered in the ANN training.

Microgrid optimal energy management problem falls into the category of mixed integer nonlinear programming. Thus, objective function may include cost functions of second or higher order polynomial equations with some start-up/shut-down decisions. Also, some complex constraints are involved to model the operational limitations of some generation/storage devices or to represent controllable loads and commitment decisions. Furthermore, considering network constraints (load flow) adds another degree of complexity to the microgrid optimal energy management problem. To handle and solve these problem formulations, heuristic optimization techniques have been applied, including Genetic Algorithms (GA) [99], [100], PSO [101], and Ant Colony Optimization (ACO) [102]; the problem formulation has also been relaxed by incorporating the inequality constraints in the objective function using penalty factors.

The minimization of total operating cost in stand-alone operation, and maximization of microgrid's revenue in grid-connected mode are two typically pursued objectives in secondary control. However, some approaches have also incorporated the reduction of Greenhouse gas (GHG) emissions as an additional objective for the microgrid operation. In this case, the energy management problem is formulated as a multi-objective optimization problem and solved with different techniques [103]. Pareto optimal solutions are investigated in [101] and [102] by using PSO and ACO techniques, respectively, while a weighted objective function that combines different individual objective functions, together with heuristic optimization techniques, are used in [104], [105].

2) Bidding: In the most typical case of centralized secondary control, the information about cost functions and operating limits of DGs is transferred to the microgrid's central controller in order to determine the appropriate system operation. However, it is possible to get a more active participation of generators and customers by allowing them to bid their power production and consumption, respectively, instead of simply communicating its cost functions and availability [95].

3) Non-Model-Based Approach: Conventional control design methods such as model-based design and simulation-based optimization may not always be adequate for a modular design that promotes plug-and-play operation, and may pose problems for the effective and fast mitigation of transients if unexpected changes in topology occur. For this reason, methods that do not require a detailed model of the system and are robust to changes in system parameters are quite appealing for microgrid control applications. Strategies used to achieve the desired adaptiveness include fuzzy controllers and ANN; however, further research is needed in this area to determine adequate design and calibration procedures of such controllers.

4) ESS Considerations: The deployment of long-term ESS, as previously mentioned, can have an important effect on the optimal operation of microgrids. In addition to balancing the demand-supply equation when power shortage or surplus are encountered, ESS can be used to maintain dispatchable DG units operating at their maximum efficiencies, and can prevent or reduce the use of expensive energy sources during peak hours, also allowing the microgrid to defer investment on new capacity. The application of long-term ESS in the remote community of Bella Coola in BC, Canada, is demonstrated in [11], [106]; it is shown in [106] that the optimal control of the Bella Coola system in the presence of long-term ESS results in almost 64% cost reduction on a typical summer day when load level is relatively low and renewable power sources are able to cover most of the demand.

In the presence of a long-term ESS, multi-stage formulations of the dispatch problem have been proposed in the literature to appropriately accommodate the storage resources [107]–[110]. In [107], a day-ahead Economic Load Dispatch (ELD) is performed for a microgrid with intermittent DGs and an ESS; the programmed dispatch is then adjusted every 15 minutes to ensure that the voltages are kept within acceptable limits, trying to maintain the dispatch of units as close as possible to the predetermined values. A more detailed formulation is presented in [108] for a microgrid with wind turbines and a hydrogen-based ESS, where the ELD is performed over several time steps, but only the results obtained for the next time step are actually implemented in the microgrid, and then the ELD is re-calculated for the following stages using a Model Predictive Control (MPC) technique.

Additional examples of the multi-stage formulation of the energy management problem applied to grid-connected and stand-alone microgrids, and using different ESS technologies, can be found in [111], [112]. In [109], the benefits from an optimal management of the ESS via multi-stage optimization are estimated to be a reduction of 5% in the operation cost, although this result strongly depends on the particular size and efficiency of the considered ESS, and the cost characteristics of the microgrid generators. The importance of adequate ESS modeling for real-time microgrid's power generation optimization applications is highlighted in [37]; it is shown that several practical complexities such as start-up conditions, impact of environmental conditions, command delays, measurement errors, and standby losses could result in the violation of storage-related constraints, and consequently, could render the microgrid optimization problems infeasible.

5) MPC: Uncertainty in the load and generation profiles has been mainly addressed indirectly in the dispatch problem by using the MPC approach, which is an optimization-based control strategy where an optimization problem is formulated and solved at each discrete time-step, and is an integral part of a centralized control approach. MPC strategies are quite appealing for energy management of microgrids, since they allow for the implementation of control actions that anticipate future events such as variations in power outputs from non-dispatchable DER units, energy prices and instantaneous demand.

In MPC, at each time-step, the solution to the optimal control problem is solved over a certain pre-defined horizon using the current state of the system as the initial state. The optimization calculates a control sequence for the whole horizon such that the selected objectives are minimized, but only the control action for the next time step is implemented; the process is then repeated at the next time-step. The implementation of MPC for solving nonlinear optimization problems at each time-step is called nonlinear MPC (NMPC).

In order to obtain the best possible results from the optimization problem, there is an incentive for using higher optimization horizons; however, the resulting optimization problem may be too big to be solved in reasonable computational times. Furthermore, the accuracy and resolution of the forecasting/prediction model typically decrease with higher horizons, which will limit the quality of the obtained solutions. A review of the main characteristics of NMPC and the stability properties of this control strategy is presented in [113], [114].

In isolated microgrids with particularly critical demand-supply balance, an MPC approach might not be enough to ensure the reliable operation of the system, and more a detailed modelling of the uncertainty might be necessary. Techniques such as robust optimization, stochastic optimization, and chance constrained optimization in combination with the traditional MPC approach offer advantages regarding the direct incorporation of uncertainty in the optimization models, which might help to achieve a more reliable operation of microgrids.

6) Communications: Centralized approaches strongly rely on fast and reliable communication systems. Moreover, most applications will require coordination between the protections and the control system [115]. In order to meet these requirements, also allowing the integration of the microgrid with the host power system, the IEC 61850 standard can be applied to the microgrid level. This standard has been designed by the International Electrotechnical Commission (IEC) Technical Committee 57, for the automation of electrical substations, and can be implemented over TCP/IP networks using the existing infrastructure (in some cases with some specific hardware), featuring response times within the range required for protection applications. The standard defines abstract data models that can be mapped to several protocols such as Generic Object Oriented Substation Events (GOOSE) and Manufacturing Message Specification (MMS). IEC 61850-7-420 describes the communication systems for DER that can be used in microgrid control applications [116]–[119].

B. Decentralized Approach

A decentralized secondary control intends to solve the energy management problem of a microgrid while providing the highest possible autonomy for different DER units and loads. Although this approach can still use a hierarchical structure for data exchange, decisions on the control variables are made locally. The autonomy is achieved using a hierarchical structure with at least 3 levels: Distribution Network Operator (DNO), Microgrid Central Controller (MGCC) and Local Controllers (LCs) [95]. The DNO is responsible for the interaction of the microgrid with the distribution network (host grid) and neighbouring microgrids and is, therefore, part of the tertiary control. The MGCC coordinates the aggregated operation of the DERs and loads within the microgrid, and is responsible for their reliable and economical operation, as well as interaction with the main grid. Finally, the LCs control DER units within the microgrid, or an aggregation of them, interacting with higher level controllers and trying to achieve local and global objectives. In a decentralized architecture, an LC can communicate with the MGCC and other LCs in order to share knowledge, request/offer a service, communicate expectations, and exchange any other information relevant to the operation of the microgrid.

Given its characteristics, decentralized secondary control systems have been primarily addressed in the literature by using the MAS framework. A MAS can be briefly described as a system composed of multiple intelligent agents, provided with local information, that interact with each other in order to achieve multiple global and local objectives. As can be expected, the connectivity of the agents, the functionalities and responsibilities assigned to each agent, and the characteristics of the information that agents can share, play an important role in the performance of the system. Agents are entities that act on the environment and have communication capability, some level of autonomy based on their own goals, and a limited knowledge of the environment (e.g., terminal measurements) [120]. An intelligent agent, which provides further distinction between a conventional power system element (e.g., a relay) and a "true" agent, is an agent that possesses the characteristics of reactivity (showing reaction to the changes in the environment), pro-activeness (seeking initiatives), and social ability (relying on communication). State estimation theory in power systems [121], [122] can be employed in the context of microgrids to address the limited knowledge of agents. Although agents can communicate, a large part of control is based on their autonomy and is performed locally.

A secondary control based on the MAS concept for microgrids was first proposed in [62], as an alternative for coordinated operation of microgrids in a competitive market environment and with multiple generator owners. The relevant microgrid actors are grouped and represented by different agents that interact in a market environment in order to determine the operation of the microgrid. In this way, consumers, generators, ESS and the main grid participate in the market by sending buying and selling bids to the MGCC based on their particular needs, availability, cost functions, technical limitations, expectations and forecasts. The MGCC is responsible for the settlement of

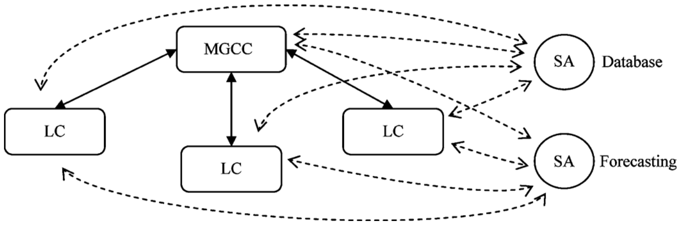


Fig. 6. MAS-based architecture with service agents.

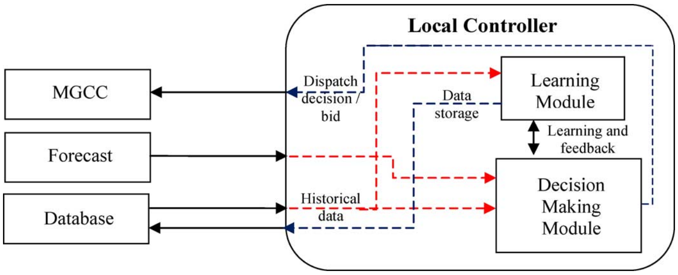


Fig. 7. Internal structure of an LC.

the microgrid market by matching buying and selling bids maximizing the social welfare, while ensuring the feasibility of the resulting dispatch. A similar MAS approach is also proposed in [123], where power flow calculations are performed to verify that the dispatch obtained in the market complies with technical standards and other operational constraints. In [124], additional agents assigned to different tasks such as load shifting and load curtailment, to allow demand side management and real power mismatches produced in the real-time operation of the microgrid, are shared by the DG units in proportion to their available unused capacity. In order to keep the design flexible, an external relational database containing the scheduling procedures is considered, and a short-term battery-ESS is also considered to balance fast changes in demand, with no participation in the market.

A secondary control using a so-called gossip-based technique, which can be considered as a special case of MAS, is proposed in [125]. According to the gossip-based control, different units exchange information regarding their operation, such as mismatches between programmed and actual power outputs, and marginal costs. To return the frequency and voltages to its original values after a system disturbance, DG units exchange the mismatches between their programmed and actual active and reactive power outputs, and calculate the average mismatch for the whole microgrid. The average mismatch is then added to the droop controllers' references to counteract the initial shift. Several strong assumptions must be made for the proposed approach to work properly, such as all droop controllers having the same droop constants, and voltage control within the microgrid being carried out from distant locations without considerable performance degradation. Optimality of the operation is obtained by progressively averaging random pairs of DG units, converging to a unique marginal cost.

Managing multi-stage operation scheduling becomes a more challenging issue in decentralized control schemes, since not all the necessary information regarding system's state, data forecast and cost functions is available to all the agents. A MAS-based architecture is proposed in [126], which includes additional agents that may enable a multi-stage operation scheduling of the microgrid. Service agents provide forecasting information and database services to the LCs to allow a better management of the energy resources over a more extended operating horizon; however, special protocols and procedures to handle the information to achieve this desired feature are yet to be studied. The architecture of a decentralized secondary control with service agents and the internal structure of an LC are shown in Figs. 6 and 7, respectively. A similar architecture is proposed in [127], which considers only generation-side bids and a sequential negotiation process; starting with the DG with lower full load average cost (FLAC), the active power mismatch for the next period of operation is negotiated with each DG in the microgrid until it is balanced.

VII. CONCLUSIONS

The development of microgrids comes as a necessity for the integration of renewable energy sources into remote communities, and as an intermediate milestone towards the realization of the Smart Grid. This paper presented an overview of current developments on microgrid control, classifying different contributions according to a defined three-level hierarchical structure. The paper reviewed the requirements and desirable traits of the control systems, its different architectures and remaining challenges; emerging approaches applied to microgrid control (e.g., MPC, MAS) were also discussed.

ESS is identified as a key technology for the integration of intermittent renewable energy sources. This, in turn, introduces major challenges to the control system for the appropriate management of this resource. Other challenges for the control of microgrids include low-inertia of power electronic-interfaced units, low X/R ratio of low voltage grids, uncertainty of generation output and unbalanced system conditions. Some of these challenges have been addressed in the literature, proposing a variety of techniques; however, robustness and adaptiveness remain an issue in most of them. In addition, effectiveness and reliability of many of the proposed control techniques is yet to be demonstrated in microgrid test systems, which is an important milestone before their implementation in real systems.

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