Microgrids

Hierarchical Control and an Overview of the Control and Reserve Management Strategies

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The increasing share of distributed generation (DG) units in electrical power systems has a significant impact on the operation of the distribution networks, which are increasingly being confronted with congestion and voltage problems. This demands a coordinated approach for integrating DG in the network, allowing the DG units to actively contribute to frequency and voltage regulation. Microgrids can provide such coordination by aggregating DG, (controllable) loads, and storage in small-scale networks, which can operate in both grid-connected and islanded mode. In this article, the islanded operating condition is considered. As in the conventional networks, a hierarchical control structure can be implemented in islanded microgrids. In recent years, many different concepts for primary, secondary, and tertiary control of microgrids have been investigated. These controllers can be classified as either local or centralized. In this article, the

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hierarchical control for application in microgrids is discussed, and an overview of the control strategies is given with respect to the reserve provision by the DG units, loads, and storage equipment.

Microgrids can provide benefits for both utility and microgrid participants.

Microgrids are independent distribution networks consisting of an aggregation of DG units, (controllable) loads, and often storage elements as well [1]. They can provide power to a small community, which can range from 1) a residential district or an isolated rural community to 2) academic or public communities, such as universities or schools to 3) industrial sites. Industrial parks can be managed as microgrids to decrease energy dependency, operate as low-carbon business parks, and increase economic competitiveness (i.e., by increasing reliability, reducing the purchase of energy, and reducing peak consumption). Microgrids can provide benefits for both utility and microgrid participants. For the utility, microgrids give scale benefits as they can be regarded as controllable entities. For consumers, microgrids enable power delivery at better power quality and high reliability. Aggregation can enable the DG units and controllable loads, which are separately too small, to take advantage from participating in the electricity markets and from providing ancillary services. In addition, aggregation in the context of market participation is beneficial to deal with the uncertainty of consumption and production. Microgrids can operate either in grid-connected or islanded mode [2].

Microgrid Control: Overview

Concerning grid control, islanded microgrids have specific characteristics that differ significantly from those of the traditional power system. First, in conventional grids, when an unbalance occurs between the generated power of the sources and the electrical power consumption, the power is instantly balanced by the rotating inertia in the system, resulting in a change of frequency. This principle forms the basics of the conventional primary control, i.e., the active power/grid frequency (*P*/*f*) droop control. Because the grid elements in microgrids are mainly power-electronically interfaced, islanded microgrids lack this significant inertia. Thus, while the conventional grid control is based on the spinning reserve, for microgrid primary control, this feature is not inherently available. Second, microgrids are connected to low- or medium-voltage networks. As low-voltage distribution grids can be predominantly resistive, the active power through a power line mainly depends on the voltage amplitude, unlike in transmission grids where the active power is mainly linked with voltage phase-angle changes across the line. Third, a large share of the microgrid generators can be fed by renewable energy sources, the intermittency of which needs to be taken into account for the microgrid control. Hence, for the control in microgrids, new control concepts have been developed [1], [3]–[8].

The hierarchical control for microgrids and especially the reserve provision related to this have been proposed recently to standardize the microgrid operation and functions [9], [10]. Three main control levels have been defined in such a hierarchy: primary, secondary, and tertiary. Figure 1 shows the diagram of the control architecture of a microgrid, which consists of local and centralized controllers and communication systems. The primary controller is responsible for the local voltage control and for ensuring a proper power sharing between multiple DG units and a stable microgrid operation. The secondary and tertiary controllers support the microgrid operation and can address multiple objectives, as discussed in the following.

The primary control is an independent local control strategy that allows each DG unit to operate autonomously. The primary controllers are responsible for the reliability of the system. Because of the fast dynamics in the microgrid, which mostly lacks a significant amount of rotating inertia, the primary controller should be fast, i.e., in time scales of milliseconds. Also, for reliability reasons, communication is often avoided in the primary control, similar to the conventional grid control. Hence, it is based only on

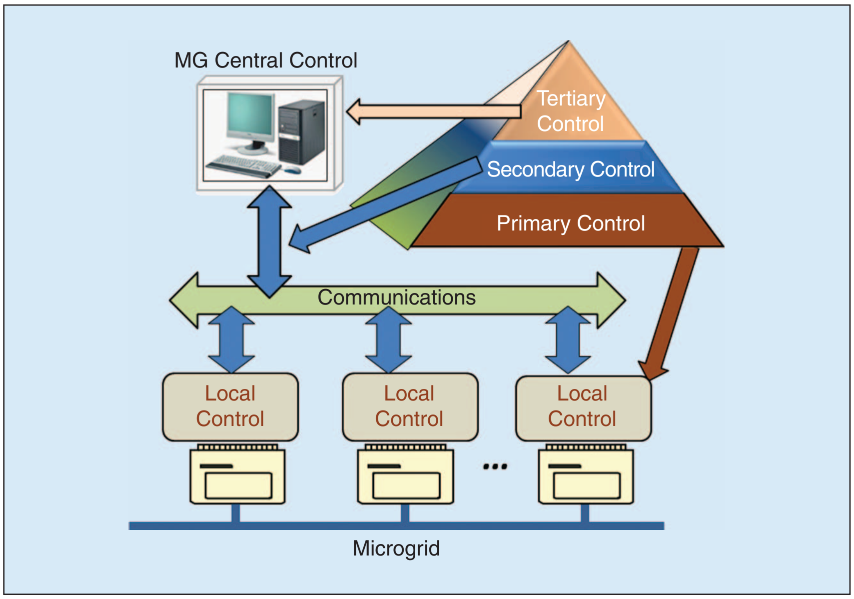

FIGURE 1 – MicroGrid communications, local and centralized controllers.

The primary control is an independent local control strategy that allows each DG unit to operate autonomously.

local measurements, being conceived as a local control strategy. With respect to the primary control, in the grid-connected mode, the DG units mostly deliver a power independent of the load variations, e.g., the amount determined by the maximum power point tracking. In islanded mode, the DG units need to dispatch their power to enable power sharing and voltage control, thereby ensuring a stable microgrid operation. Different variants for primary control without interunit communication exist, including droop control, virtual synchronous generators (VSGs), and virtual impedances. Reserve provision is discussed for the droop controllers, and in this context, a distinction is made between the grid-following and the grid-forming reserve by the droop-controlled DG units.

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To achieve global controllability of the microgrid, the secondary control is often used. The conventional approach for secondary controllers is to use a microgrid central controller (MGCC), which includes slow control loops and low-bandwidth communication systems to sense the key parameters in certain points of the microgrid, and sends the control output information to each DG unit [9], [10]. This centralized control concept was used in large utility power systems for years to control the frequency of a large-area electrical network and has been applied to microgrids in the last years for voltage and frequency restoration [11]–[13]. Furthermore, other objectives regarding voltage control and power quality, such as voltage unbalance and harmonic compensation using the secondary controller, have been proposed recently [14]. A method for increasing the accuracy of the reactive power-sharing scheme has been presented in [18], which introduces an integral control of the measured load bus voltage, combined with a reference that is drooped against the local reactive power output. The active power sharing has been improved by computing and setting the phase angle of the DGs instead of its frequency in the conventional frequency droop control and by using communication [19].

Although secondary control systems have conventionally been implemented in a centralized manner in the MGCC, distributed control strategies can be implemented as well [15]. A multiagent system (MAS) can be applied for voltage and frequency restoration in a distributed manner [16], [17]. On one hand, the use of MAS technologies allows the intelligence of the control system to be distributed in a decentralized way, where local controllers have their own autonomy and are able to take their own decisions. On the other hand, a central controller holds the control intelligence that considers the microgrid as a whole and is able to optimize the operation of the entire microgrid.

As opposed to the primary control, which needs to be designed specifically for application in islanded microgrids, the secondary and tertiary controllers are generally based on similar controllers used in the (smart grid) power system and in energy management systems (EMSs) in buildings and business areas.

The MGCC can also include tertiary control, which is related to economic optimization, based on energy prices and electricity markets [9]. Furthermore, the centralized tertiary controller exchanges information with the distribution system operator (DSO) to optimize the microgrid operation within the utility grid. When connected to the grid, this control level takes care of not only the energy and power flows but also the power quality at the point of common coupling (PCC).

Reserve Provision: Overview

As microgrids are often regarded as small pilot versions of the future electric power system, the reserve provision in islanded microgrids adds significant value not only in these microgrids but possibly in the entire power system as well. Microgrids have the potential to play a key role in facilitating the integration of DG and will act as the initial proving ground for demand response, energy efficiency, and load-management programming. In this context, the provision of prep-rimary and primary reserve by the grid elements, i.e., generators, loads, and storage elements, is discussed. Furthermore, the grid elements' primary responses are classified in the grid-forming and grid-following reserve provision [20]. In a conventional power system, the spinning reserves are provided by the online generators that use a frequency droop to react on frequency changes. The secondary frequency control brings the frequency back to its nominal value. Actions of the primary control reserves need to be taken within 5–30 s, and the secondary reserves reset the primary control reserves in 5–15 min. A major challenge in the islanded microgrids, and the future power systems with large amounts of renewable sources, is the reserve management as it cannot be merely delivered by online dispatchable units. Therefore, in this article, for the primary reserve, a distinction is made between the grid-forming and grid-following reserve. This distinction is mainly dependent on the order in which they are committed. The grid-forming reserve is allocated primarily by the dispatchable units. The grid-following reserve is allocated next when the grid-forming reserve is no longer sufficient. It can, for instance, consist of deviation from the maximum power point in photovoltaic (PV) panels or shifting the consumption. Another issue in microgrids is the low amount of rotating inertia. Therefore, next to the primary reserve, preprimary reserve needs to be provided. The preprimary reserve reflects the reserve that is automatically allocated in the first seconds after a load variation before the actual primary reserve takes action. In conventional systems, this is present in the rotating inertia of the directly coupled generators and motors and limits the frequency deviations immediately after a load variation.

Local Control

The control of uninterruptible power supplies (UPSs) can be regarded as the starting point for the islanded microgrid control. Like in microgrids, the UPS control involves the optimal control of a converter interface. While UPSs generally consist of a single generating or storage unit, microgrids include multiple DG units. Hence, the islanded microgrid requires an adequate power sharing strategy between the units. However, the most striking difference is the scale of both systems: compared to UPSs, microgrids are significantly larger. Hence, avoiding a communication link for the primary control is crucial in microgrids, as opposed to UPS control, which is often based on master/slave and centralized control [21]. The reason is twofold. First, building a new communication infrastructure for the primary control can be uneconomical. Second, and more importantly, a communication link induces a possible single point of failure that can affect the reliability of the system. The controllers that avoid communication between the units generally rely on a droop control concept. Hence, in this section, different droop control strategies and the reserve provision added by these droop controllers will be discussed.

Microgrids have the potential to play a key role for facilitating the integration of DG and will act as initial proving grounds for demand response, energy efficiency, and load-management programming.

For the local primary control without interunit communication, the units can be classified as either grid following or grid forming. The grid-following units are current controlled, i.e., their reference current is extracted from the measured terminal voltage combined with the available dc-side power. Often, the dc-side power is changed based on the state of the primary energy source and not based on the state of the network, e.g., the maximum-power point tracking for wind and solar generation, the heat-driven control of a combined heat and power (CHP) units, and biomass generation at nominal power to achieve maximum efficiency of the plant. Including primary reserve in such units leads to a change of the dc-side power based on the local grid parameters. This kind of primary reserve, called the *grid-following reserve*, can be implemented in the DG units and also in the loads through demand response programs. It is only allocated when the grid-forming reserve gets depleted. The grid-forming DG units are voltage controlled, i.e., their reference voltage is extracted from the active and reactive power controllers. These units are responsible for the voltage control and power sharing in an islanded system. Hence, their dc-side power depends on the state of the network. Primary reserve in such units means that, in steady state, there is still some guaranteed reserve to inject more or less power. This kind of primary reserve, called the *grid-forming reserve*, can also be implemented in storage units.

The main difference between the grid-following and grid-forming reserve is the order in which they are committed. Primarily, the grid-forming reserve will be addressed, and the grid-following reserve will be used only for larger events. As microgrids contain a large share of intermittent DG units, the need for grid-following reserve is more urgent compared to the conventional large-scale power systems. If the reserve of the dispatchable units and the storage capacity is depleted, the grid-following units will address their reserve. The loads can react in a demand response program or renewables can deviate from their maximum power point.

Single Grid-Forming Unit

If there is only one grid-forming unit in an islanded microgrid, this unit can be equipped with simplified voltage control with a predefined reference voltage. This is analogous as in UPSs with one back-up unit. It is not possible to connect multiple grid-forming units with the predefined reference voltage to a single network. This would lead to synchronization problems, circulating currents, and inaccurate power sharing (i.e., a power delivery that is not according to the ratings or droops of the units). Hence, all other units need to be grid following. The grid-forming unit is solely responsible for the power balance in the network. For example, grid-forming inverters with battery storage or diesel generators that can enable stand-alone operation are already available in the market. The primary grid-forming reserve is available as long as the battery storage or available diesel remains sufficient. Generally, the primary grid-following reserve is not yet available in practice. However, new grid-following DG units are sometimes already equipped with the primary grid-following reserve. An example is the frequency response in the grid-following PV inverters. The grid-forming

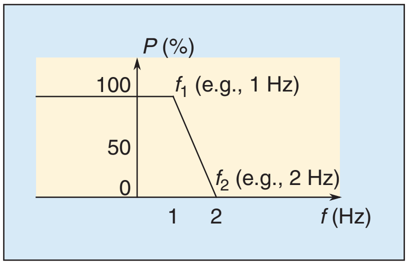

FIGURE 2 – Grid-following inverter with P/f characteristic.

inverter raises the grid frequency in case of a low load and high storage level. The grid-following units respond to this change of frequency by linearly decreasing their output power as shown in Figure 2. The legislation for this has only recently been developed. In Belgium, for example, Synergrid (the federation of network operators for electricity and gas) has recently changed the grid codes (revision of C10/11 grid code [22]). Before this change, if the frequency increases above 50.2 Hz, the converters (PV) had to shut down. Starting in July 2012, a linear power decrease from the nominal power (maximum power point) at 50.2 Hz to shut down at 51.5 Hz has to be implemented.

Multiple Grid-Forming Units: *P/f* Droop Control

In case a microgrid is fed by multiple dispatchable DG units, the power needs to be shared, e.g., according to the ratings of the units. For UPSs, some control schemes for power sharing have been proposed such as master/slave and centralized control [21], [23], [24]. These control strategies rely on a communication link between the DG units. The droop control method is widely used for the primary control in islanded microgrids as it does not rely on interunit communication. The droop control in microgrids mimics the conventional grid control, which is based on the well-known P/f and Q/V droop controllers in Figure 3(b). In the conventional network, the large synchronous generators (SGs) provide a significant rotating inertia in the system; hence, changes of grid frequency indicate a difference between the electrical power consumption and the mechanical input power. All generators act on frequency through their P/f droop controllers. However, in microgrids, most DG units are converter interfaced to the network. Consequently, islanded microgrids lack the rotating inertia on which the conventional grid control is based, and P/f droop control, if based on the inertia alone, is not possible. However, in inductive networks (Figure 4), the power flow equations show an intrinsic linkage between the active power and the phase-angle difference, and between the reactive power and the rms grid voltage. As frequency dynamically determines the phase angle, P/f and Q/V droop controllers, analogous to those in the conventional network, can be used in the dispatchable DG units of inductive microgrids [Figure 3(b)].

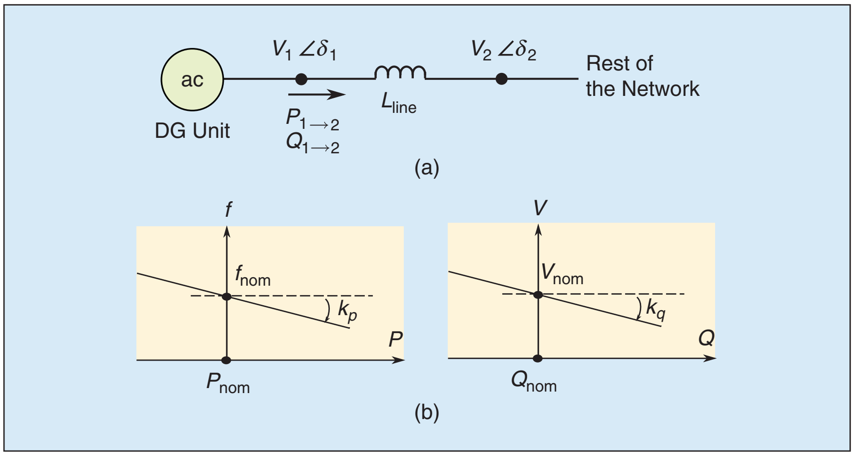

FIGURE 3 – The P/f droop control: (a) $P-f$ linkage $Q-V$ linkage in resistive networks and (b) $P-f$ and $Q-V$.

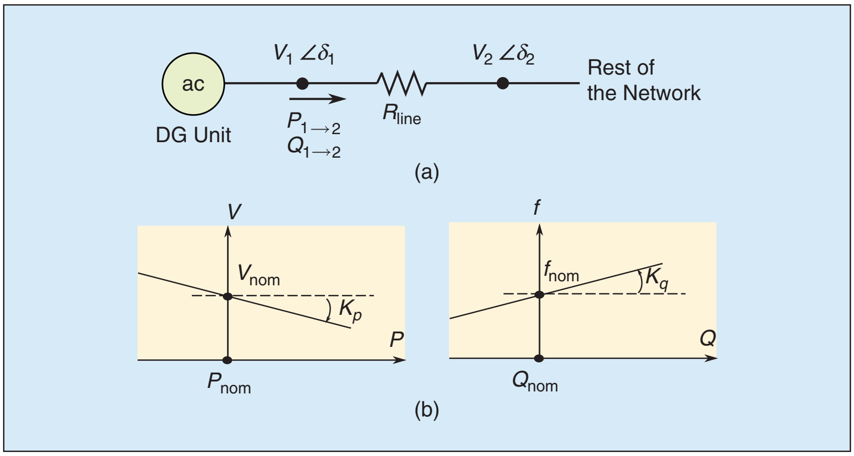

FIGURE 4 – The P/V droop control: (a) $P-V$ linkage $Q-f$ linkage in resistive networks and (b) $P-V$ and $Q-f$ droop controllers.

Variants in *P/f* Droop Control

In the traditional power system, a $P(f)$ droop is implemented, where f is measured to determine the desired input power. In a microgrid, with droops not depending on inertia, an analogous $f(P)$ characteristic can be implemented as well. The ac power is measured to determine the frequency of the unit. Hence, measurements of the frequency f are not required.

Some improvements on the traditional droop control method are summarized below. To deal with the presence of some resistance in the inductive lines, in [5], the output impedance of the inverters is controlled, and in [25], reference frame transformation is applied.

Other modifications are the adaptive droops [26], the hybrid droop controllers [27], and the modified droop controllers [28].

Primary Reserve

The assignment of the primary grid-forming reserve is analogous as in the conventional network. In steady state, the droop-controlled DG units need to have some reserve to inject more or less power when required by the grid. Dedicated storage solutions providing the grid-forming reserve may include battery storage or flywheel energy storage, an example of which is given in [29].

Renewables are not considered grid-forming units; hence, they only provide the grid-following reserve. Concerning the grid-following reserve, several potential solutions exist. The first is the frequency response of large wind farms. In case of high frequencies, the wind turbines can be committed to the primary control by lowering their output power [30], [31]. In case of low frequencies, storage and load shifting present a high opportunity, which still needs to be explored extensively. Thermal buffering in the loads can be used as well, e.g., (industrial) freezers can be dynamically controlled, triggered by the frequency to provide the primary reserve [32]. However, deterministic control schemes prove to be inadequate, as the consumption of different individual appliances tends to synchronize. Therefore, in [33], the decentralized random controllers are used for the dynamic-demand control based on the grid frequency. In [34], frequency response is included in electrical vehicles in islanded microgrids. Both a frequency droop mechanism and a central control mechanism are presented.

Preprimary Reserve/Inertial Response

In normal operating conditions, the frequency is limited by the narrow margins of the local primary controllers, the presence of rotating inertia in the system and the frequency-dependent consumption of, e.g., electrical motors. The primary control stabilizes the frequency after an event but has no significant effect on the initial frequency deviations. As the number of directly coupled generators and loads is steadily decreasing, the available inertia decreases (certainly in islanded microgrids) [35]. This lower inertia results in faster and larger frequency deviations after an event, which may cause problems in the network [36]–[38]. To emulate rotating inertia, the DG units can be operated as VSGs, to damp initial transients and stabilize the system.

VSGs Based on Frequency Measurements

In [36], the VSGs have inertial response to slow down the frequency variation, which gives time for the primary controllers. These VSGs are based on frequency measurements and estimations. The inertial response is derived from

$$P^{*}_{\mathrm{VSG}} = -J_{\mathrm{VSG}}\hat{\omega}\frac{\mathrm{d}\hat{\omega}}{\mathrm{dt}}, \qquad (1)$$

where J_{VSG} is the virtual moment of inertia and the pulsation $\hat{\omega}$ and $\mathrm{d}\hat{\omega}/\mathrm{dt}$ are estimated using a linear Kalman filter, which is based on a combination of a random walk and a random ramp process to model the frequency deviation from its nominal value [39]. The slope of the linear (random ramp) curve represents the estimated average rate of frequency change. An overview of applications, including microgrids and the implementation of Kalman filters, is provided in [40].

The VSG requires a short-term energy-storage system added to the inverter to provide virtual inertia to the system. The additional P^{*}_{VSG} exchange with this storage element is determined in (1). The total power is determined according to

$$P_{\mathrm{tot}} = P_{\mathrm{ref}} + P^{*}_{\mathrm{VSG}} + P^{*}_{\mathrm{droop}}. \qquad (2)$$

P^{*}_{droop} is determined by the primary controller, for example, a P/f droop. Likewise, in [41], a virtual inertia controller is discussed, which also changes the power exchange with an energy storage system proportional to the derivative of the grid frequency. However, instead of being constant, the virtual inertia J_{VSG} is adaptive to the situation. In synchronverters, which are similar to VSGs, the electrical and mechanical models of an SG are derived such that the system dynamics observed from the grid side will be those of an SG [38]. The energy storage on the dc-bus emulates the inertia of the rotating part of the SG. This may come in strong bursts as it is proportional to the derivative of the grid frequency [38].

VSGs Based on Power Measurements

Another method to implement VSGs is by using power measurements to determine the reference phase angle of the inverter [37] as

$$P_{\mathrm{in}} - \hat{P}_{\mathrm{out}} = J\omega^{*}_{n}\frac{\mathrm{d}\omega^{*}_{n}}{\mathrm{dt}} - Ds, \qquad (3)$$

where D is the damping factor, J is the inertia moment, ω_n is the angular velocity of the virtual rotor, s is the slip, $s = \omega_{\mathrm{n},0}\Delta\omega^{*}_{n}$, and $\omega_{\mathrm{n},0}$ is the synchronous angular velocity. The value $\hat{P}_{\mathrm{out}}$ is the measured ac power of the inverter and P_{in} is a known value, e.g., the nominal power of the unit, the maximum power point, or the active power determined by a P/f droop controller. In a grid-following VSG, P_{in} is constant. In a grid-forming VSG, P_{in} can be determined according to a P/f droop function. To determine ω^{*}_{n}, from which the inverter's phase angle θ^{*} is calculated, (3) is used. The reference voltage is calculated using this phase angle. The DG system consists of an energy source, a storage element, and an inverter in series. The energy storage compensates differences between P_{in} and P_{out}. The inertial term represents the virtual kinetic energy, and the damping term represents the fluctuation of P_{in} and P_{out}. In [42], the DG system consists of a PV panel and fuel cell to mimic the performance of an SG in a VSG based on power measurements.

Other Methods

Instead of using an additional storage element for the preprimary reserve, other methods exist that can be included in the loads, storage, and generators. A first example is a wind turbine with an additional preprimary reserve support function in

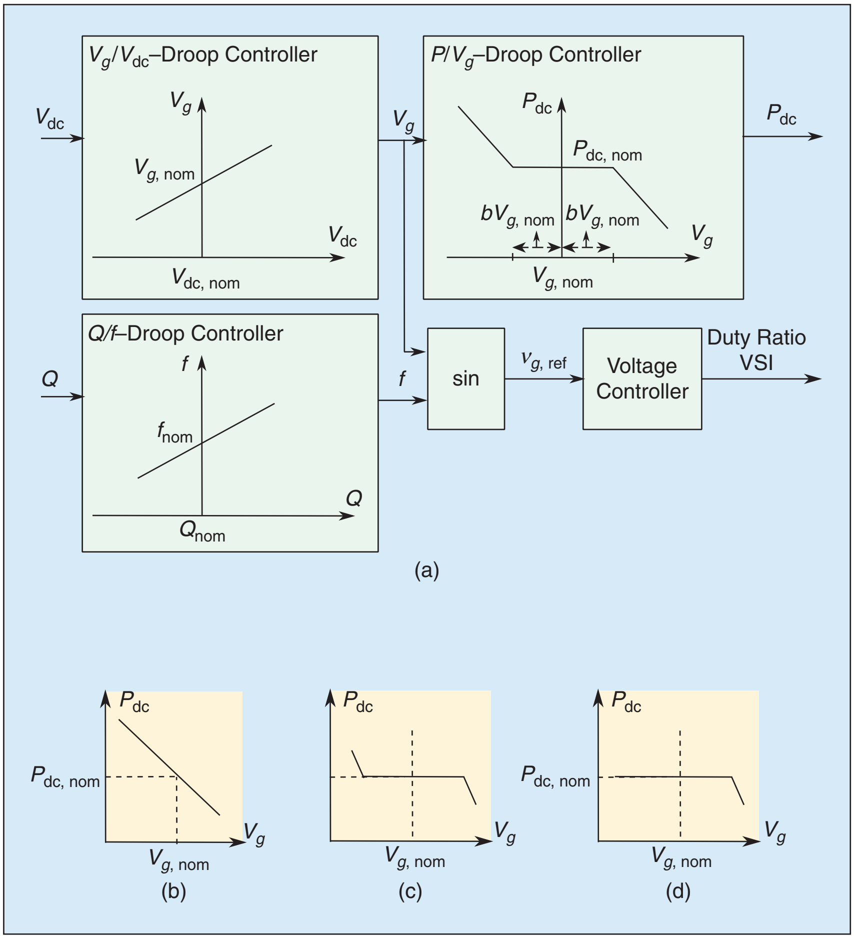

FIGURE 5 – VBD control. (a) Control strategy. (b)–(d) Constant power bands of dispatchable versus less dispatchable DG units: (b) a fully controllable unit, (c) a less controllable unit, and (d) a renewable energy source (without storage or controllable consumption).

[43], also called the *inertial response of wind turbines.* This wind turbine is controlled to supply additional power that is drawn from the energy that is mechanically stored in the rotor. This can provide an increase in the generated power over the critical first few seconds after a large frequency drop. Second, in [35], a control algorithm based on the power-frequency behavior of a virtual synchronous motor is applied to electrical vehicle charging. Based on the demanded power, the steady-state power is calculated as a function of the frequency. A frequency gradient is also included.

Multiple Grid-Forming Units: P/V Droop Control

Based on the line characteristics, the P/f droop controllers are generally not applicable in low-voltage microgrids. The low-voltage lines typically have a high R/X value [44]. In predominantly resistive networks (Figure 4), there is a main linkage between P and V and between Q and f. Hence, the droop control strategies need to be reversed in the resistive microgrids, leading to the P/V and Q/f droop controllers depicted in Figure 4(b) [45].

Variants in *P/V* Droop Control

An improvement on the P/V droop control strategy is obtained by including a resistive virtual impedance in the converter to deal with the presence of some inductance in the predominantly resistive lines. This virtual output impedance loop fixes the output impedance of the inverter, increases the stability of the system, and enables sharing of linear and nonlinear loads [5]. A resistive output impedance provides more damping in the system [46] and complies with the P/V droop control strategy of the generators. When determining the R/X value of the lines, the inductance of the inductor or the transformer that sometimes connects the DG unit to the grid should be taken into account if the controlled grid voltage is the one before this inductive element, from the DG unit's point of view. This may decrease the R/X value of the system seen by the DG unit [5].

Similar to the Q/V droops in the conventional grid control, there is a tradeoff between voltage control and active power sharing when applying the P/V droop control method. If power sharing precisely according to the ratings of the DG units is more important, an overlaying controller can change the set points of the primary controller, as discussed in the "Line Impedance Independent Power Equalization" section.

Another variant of the traditional P/V droop control is the voltage-based droop (VBD) control shown in Figure 5(a) [7]. For the active power control, this droop controller consists of a combination of a V_g/V_{dc} droop controller and a P/V_g droop controller, with V_{dc} the dc-link voltage, and V_g the terminal voltage of the DG unit. The former enables power balancing of the DG unit's ac and dc side and an effective usage of the allowed tolerance on the variations of terminal voltage from its nominal value for grid control. It is based on the dc-link capacitor of the converter taking the role of the rotating inertia in conventional grid control [47]. In this way, changes in the dc-link voltages indicate a difference between the ac-side power injected into the microgrid and the input power from the dc-side of the inverter, which is analogous as the frequency changes in the conventional power systems. The P/V_g droop controller avoids voltage limit violation and is combined with constant-power bands with a width $2b$ that delay the active power changes of the renewables (wide constant-power band) compared to those of the dispatchable DG units (small

TABLE 1 – THE MEASUREMENT RESULTS OF VBD CONTROLLER FOR DIFFERENT LOADS AND WIDTHS *b* OF THE CONSTANT-POWER BAND IN THE VBD CONTROLLER.

CASE	LOAD (Ω)	UNIT	b (%)	$I_{\mathrm{dc,nom}}$ (A)	I_{dc} (A)	V_{dc} (V)	V_g (V)	P_{DG} (W)
1	27	1	∞	1	1	185.9	146.0	183
		2	∞	1	1	188.4	148.3	183
2	13	1	∞	1	1	120.0	80.1	111
		2	∞	1	1	121.1	81.1	107
3	13	1	∞	2	2	181.0	141.1	340
		2	∞	2	2	184.2	144.2	342
4	13	1	0	2	2.8	180.8	141.0	471
		2	∞	1	1	169.9	119.9	160
5	13	1	0	2	2.5	186.3	146.5	445
		2	∞	1.5	1.5	181.3	144.4	266
6	27	1	0	2	1.5	212.9	173.2	300
		2	∞	1	1	212.1	172.3	206
7	13	1	0	4	3.5	205.9	166.2	686.5
		2	∞	1	1	189.5	149.7	180.9

constant-power band) to more extreme voltages [Figure 5(b)].

Table 1 and Figure 6 show some measurement results of the VBD controller. The measured DG unit terminal voltage of case 7 is depicted in Figure 6(a), and the accuracy of the voltage tracking is illustrated in Figure 6(b). The microgrid test setup consists of two DG units connected to a load. The load consists of either a 13 or 27 Ω. The inverters of the DG units have been realized by using a printed circuit board (PCB) that was developed in Ghent University. The switches consist of insulated-gate bipolar transistors (IGBTs) with a maximum collector–emitter voltage of 1200 V and a collector current of 40 A. The dc side of the inverter, i.e., the energy source, is emulated as a dc current source by means of the Sorensen SGI6000/17C source. The dc bus consists of a cascade of two in parallel connected electrolytic capacitors (hence, four capacitors in total). Each capacitor has a nominal voltage of 500 V and a capacitance of 1000 mF. An FPGA Spartan 3E 1600 is used for determining the PWM signals of the DG units. The configuration is performed with the System Generator toolbox for Simulink/Matlab of Xilinx. In the measurements, an I_{dc}/V_g droop controller is included, analogous to the P/V_g droop controller, with I_{dc} the dc-side current, $I_{\mathrm{dc,nom}} = 2$ A, $V_{\mathrm{dc,nom}} = 200$ V, $V_{g,\mathrm{nom}} = 160$ V, the droop of the I_{dc}/V_g droop controller equals -0.04 A/V and the droop of the V_g/V_{dc} droop controller equals 1 V/V.

The DG units are operated as current sources, and the effect of a changing load and dc current are measured. When comparing cases

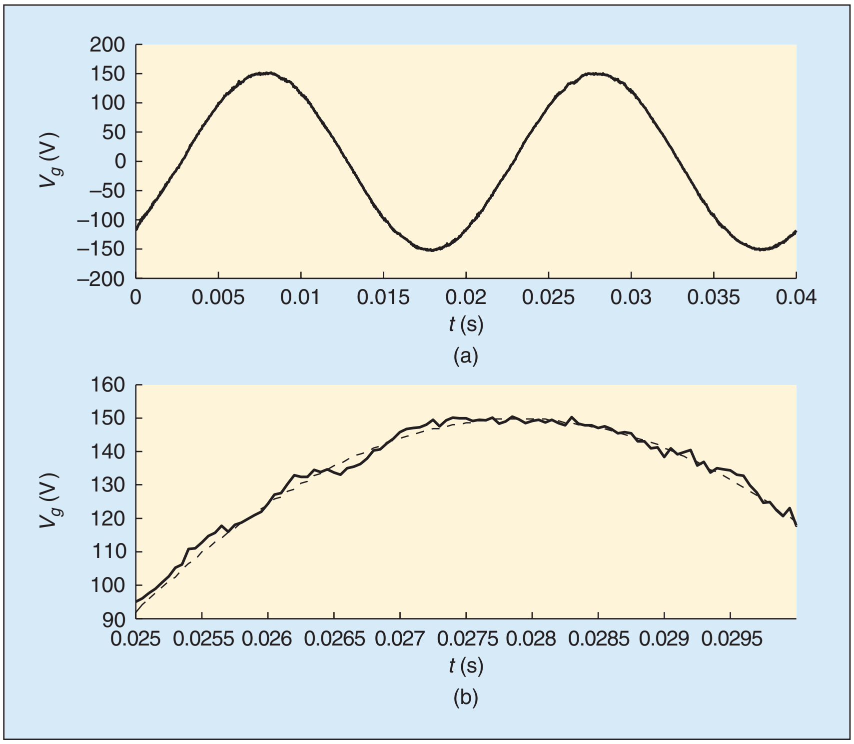

FIGURE 6 – The voltage tracking results in a two-DG unit microgrid with VBD control. (a) Voltage profile. (b) Voltage tracking.

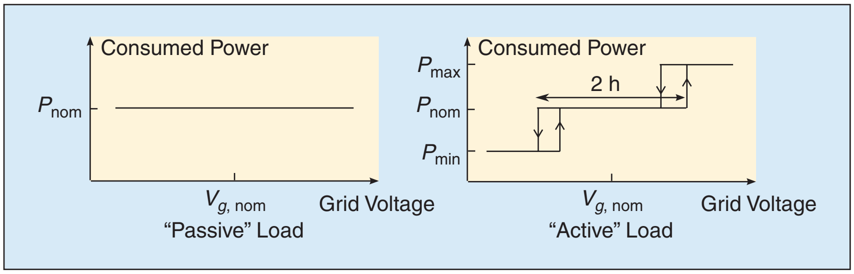

FIGURE 7 – The grid-following reserve in the loads.

1 and 2, the load has significantly increased in case 2. This is clearly visible in the lower grid voltage because of the large constant-power band of the DG units that are here undispatchable. Hence, the microgrid balancing is done by changing the grid voltage with the V_g/V_{dc} droop controller. For example, in a larger solar irradiation in case 3, the voltage is closer to its nominal value. However, this is not a sustainable option, as a small microgrid needs some flexibility for maintaining a proper voltage quality.

Therefore, in the cases 4–6, DG1 is dispatchable, while DG2 remains with large constant-power band. Hence, $I_{dc,1}$ is determined by the I_{dc}/V_g droop controller and $I_{dc,2}$ is still solely determined by the primary energy source. When comparing cases 4 and 6, indeed DG1 captures the changing load. In the case 4, the voltage is clearly closer to its nominal value compared to case 2, because of the dispatchable nature of one DG unit.

When the rating of DG1 doubles in case 7, i.e., $I_{dc,1,nom} = 4$ A instead of 2 A, the delivered power by this unit of course increases. However, it does not double as the unit is dispatchable and contributes in the voltage control of the islanded microgrid.

Primary Reserve

When using the traditional P/V droop control strategy, the primary reserve identification is analogous as in the P/f droop control, except for a change of trigger for the reserve allocation from the frequency to grid voltage. The VBD control can automatically assign the primary reserve provision in a hierarchical structure by setting the constant-power bands. Based on the terminal voltage, the order for power changes can be: 1) the dispatchable DG units, 2) the assigned storage, 3) the highly controllable loads, 4) the less dispatchable DG units (including local storage, maximum power point changes, and local load changes), and 5) the less controllable loads. To what group a specific grid element is assigned can vary in time depending on the constraints of the unit. The usage of VBD control with constant-power bands enables the local network state to be clearly visible in the terminal voltage. High voltages are present in case of high renewable injection and low load. Low voltages indicate low renewable injection and a high load, combined with a low reserve for more power injection from the dispatchable DG units. For example, the loads shift their consumption toward high-voltage times [48] as shown in Figure 7.

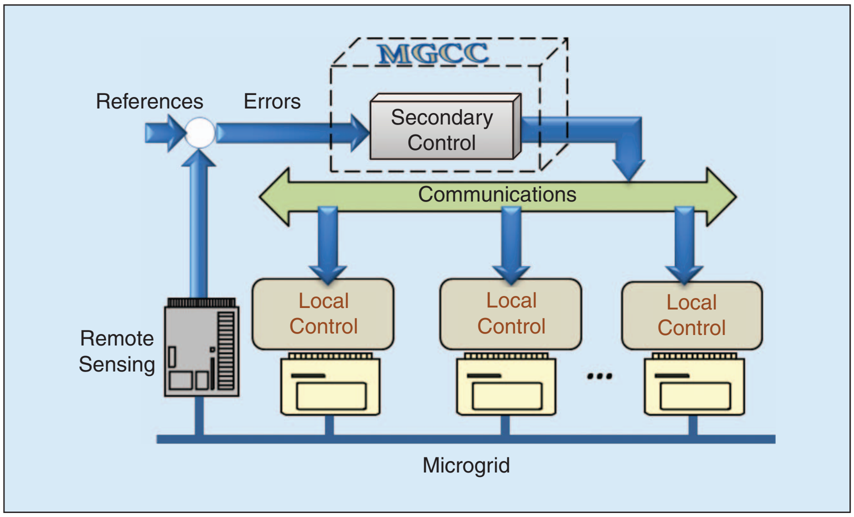

FIGURE 8 – A centralized secondary controller.

Preprimary Reserve

In the conventional power system and in P/f droop-controlled microgrids, the preprimary reserve concurs with the inertial response of the units. Hence, large rotating inertia in the system implicates a large amount of preprimary reserve. In the P/V droop-controlled microgrids, this reserve is provided by the dc-link capacitors of the DG units and other microgrid elements.

Discussion

The primary control reserve is crucial in the network exploitation, now and even more in the future networks, and both in the grid-connected and islanded operation. The primary control reserve enables a stable operation of the network. Hence, it is primordial for the grid control. However, many distributed and/or intermittent generators currently do not yet contribute to the primary reserve (except for, e.g., new large wind farms that need to curtail power to mitigate an increasing frequency). Hence, either the large generators should exploit more reserve to compensate for this lack of reserve in the DG units, or other kinds of reserve should be allocated. Because of the small scale of the microgrids, dynamic problems are often an even larger challenge in islanded microgrids than in the conventional electric power system. The load factor, i.e., the ratio of average load to maximum load, can be small. Hence, during the peak times of load and low renewable energy input, the inverters' current capability can get saturated. A good energy management strategy for the loads and storage elements in a centralized tertiary controller based on accurate forecasts should tackle these issues.

As discussed, technically, the primary reserve can be provided by the DG units by changing their control strategies, which requires specific new regulations. Another method to force the DG units to provide the primary reserve is by including this into the market. However, currently, most DG units are too small to participate in the markets and hence cannot benefit from the primary reserve provision. A solution is to aggregate DG units into virtual power plants and microgrids, providing them scale benefits for, e.g., the primary control (reserve) market participation.

An increased flexibility will also need to be provided by the loads. Loads can contribute to the primary reserve by including demand response programs [49]–[52], preferably with the local control strategies. The centralized demand response programs enable the loads to add to the secondary and tertiary reserves provision. These programs can be based on push methods (direct load control) or pull methods (economically driven). For the pull methods, the trigger is a time-variant price. The advent of electrical vehicles can add significant flexibility to the network by using the batteries as energy buffer (change the charging times) or as distributed energy storage elements (bidirectional power exchange with the network).

Adequate reserve provision, not only by DG units but by all grid elements, is crucial for a secure islanded microgrid operation. Because of their small scale and high levels of intermittent power sources, microgrids provide a unique opportunity for investigating and addressing challenges in the future electric power system, which is increasingly being confronted with balancing (reserve) and congestion problems.

Centralized Control

The MGCC often includes a centralized secondary control loop [53]. The secondary controller has various responsibilities, such as frequency and voltage control as well as improving the power quality through unbalance and harmonics mitigation. Figure 8 shows a microgrid hierarchical control architecture. It consists of many DG units controlled locally by a primary control and a centralized secondary control. The latter measures from a remote sensing block, i.e., centralized control, a number of parameters to be sent back to the controller by means of a communication system. These variables are compared with the references to obtain the error to be compensated by the secondary control, which will send the output signal through the communications channel to each of the DG units' primary controller. The advantage of this architecture is that the communication system is not too busy since messages are sent in only one direction (from the remote sensing platform to the MGCC and from the MGCC to each DG unit). The drawback is that the MGCC is not highly reliable since a failure of this controller is enough to stop the secondary control action. The distributed secondary control addresses this issue [15]. Every DG unit has its own local secondary controller, which can produce an appropriate control signal for the primary control level by using the measurements of other DG units, e.g., to achieve frequency and voltage restoration. In [15], the impact of communication and communication latency are considered, and the results are compared with the conventional MGCC. The failure of a DG unit will affect only that individual unit, and other DG units can work independently. Thus, adding more DG units is easy, making the system expandable. However, still having an MGCC is mandatory to achieve other purposes such as coordination of the MG units in black start process or energy management.

In summary, the primary and tertiary controls are decentralized and centralized control levels, respectively, since while the primary control is taking care of the DG units, the tertiary controller is concerned about the global microgrid optimization. Although the secondary control systems conventionally have been implemented in a centralized manner, in the MGCC, it also is possible to have it distributed along the local control with communication systems. This kind of distributed control is also named a networked control system (NCS) [54], [55].

Frequency Control

Traditionally, in large power systems, the secondary controllers provide frequency restoration by changing the output active power. The frequency is highly dependent on the active power as most generators in these systems are directly coupled to the grid. This fact is an advantage since frequency is a control variable that provides information related to the consumption/generation balance of the entire grid. This central controller, named load–frequency control (LFC) in Europe or automatic generation control (AGC) in the United States, is based on a slow proportional-integral (PI) control with a deadband that restores the frequency of the grid when the error is higher than a certain value, e.g., ±50 mHz. A similar concept has been implemented in the MGCC to restore the frequency of a microgrid consisting of P/f droop-controlled DG units or the aforementioned variations such as VSGs [53].

The voltage can be controlled by using a similar procedure as the secondary frequency control in the traditional electric power system.

Voltage Control

The voltage can be controlled by using a similar procedure as the secondary frequency control in the traditional electric power system [9], [10]. When the voltage is outside a certain range of nominal rms values, a slow PI control compensates the voltage error in the microgrid, passing it through a dead band, and sending the voltage information by using low-bandwidth communications to each DG unit. Thus, it can be implemented together with the frequency restoration control loop at the MGCC. This approach can also be extended to more resistive microgrids by using the P/V droops in the primary control, and restoring the voltage of the microgrid by sending the voltage correction information to adjust the voltage reference. The secondary control is transparent to the R/X nature of the power lines, as opposed to the primary control.

There is also an increasing interest in using DG units not only to inject power but also to enhance the power quality. The voltage unbalance compensation and harmonics mitigation can be dealt with by a local controller [56]. Also, the secondary controllers can be used for power quality improvement at specific locations such as sensitive load buses [57] and compensation of voltage unbalance at the PCC [58]. These secondary controllers send proper control signals to the DG units' local controllers.

Line Impedance Independent Power Equalization

It is well known that in a low-R/X microgrid, it is difficult to accurately share the reactive power, and the same effect occurs when trying to share active power in high-R/X microgrids. The reason is that as opposed to the frequency, the grid voltage V can be different in different network locations, which can affect the power sharing ratio. Therefore, in the P/f-Q/V droop control, the reactive power sharing ratio may differ from the droop ratio, which is here called *inaccurate reactive power sharing*. Similarly, the active power sharing ratio can differ from its nominal value in the PV-Q/f droop controllers. Several solutions to increase the power sharing accuracy have been presented in literature. First, these controllers can operate on the primary control level, such as the reference frame transformation method in [25]. Similarly, the primary $Q/\dot{V}$ droop control method, where $\dot{V}$ represents the time rate of change of the voltage magnitude V, improves the reactive power sharing of the conventional Q/V droop control that deteriorates due to its dependence on the line impedances [59]. To compensate for the errors due to the different voltage drops along the electrical network of a microgrid, a small ripple injected by the converters can be used as control signal [60]. However, this method is difficult to be applied with microgrids that contain more than two DG units, and the circuitry required to measure the small real power variations in this signal adds to the complexity of the control [18]. Second, the controllers can operate on the secondary control level. In [18], each unit regulates its terminal voltage based on the reference voltage that is obtained from, first, the conventional Q/V droops and, second, a correction term based on the measured load voltage. An analogous method to achieve accurate power sharing by introducing load voltage feedback is presented in [61]. Alternatively, a possible solution is that each DG unit sends the measured Q (or P in high-R/X microgrids) to the MGCC to be averaged and sent back to each unit as a Q reference from the droop control [62].

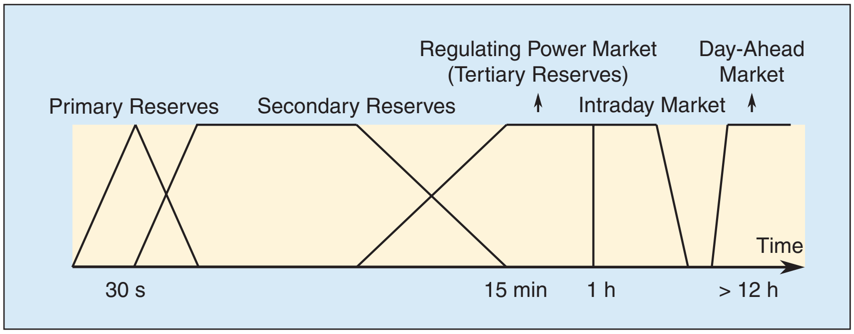

FIGURE 9– An overview of the Danish electricity markets.

Secondary Reserve

Microgrids can supply ancillary services that can be used for the primary reserve provision, as explained before. They can also provide secondary and tertiary reserves aggregated in more DG units altogether. The same techniques and methodologies of the primary reserves can easily be extended to secondary and tertiary reserves. However, they would then be widely distributed on the network with multiple microgrids and, therefore, exposed to serious controllability and security issues [20]. Indeed, the local droop controllers could be implemented to react to the system frequency changes. The predetermined droops work well for reserve markets with long-term contracts (for more than one day). However, in short-term markets, it is necessary to aggregate the information from an MGCC, which also receives information from the distributed network operator (DNO).

The most advanced country in the terms of including CHP units in delivering ancillary services and balancing is Denmark. The success of involving distributed CHP for balancing tasks is because the transmission system operator (TSO) has organized the balancing markets in a way that matches these plants. The Danish electricity markets are shown in Figure 9. The TSO has organized the primary reserve market as a day-ahead market, split into six 4-h periods and split this into a market for positive primary reserve and a market for negative primary reserve. An example can be found in the Skagen distributed-CHP plant located in Frederikshavn municipality at the northern tip of Denmark [63], which has three 4-MW natural gas CHP units, heat storage, a gas peak load boiler, and a 10-MW electrical boiler. The plant receives heat from a waste incineration plant as well as waste heat from industry and is now considering investing in a large-scale heat pump.

Tertiary Control

The tertiary control level, and correlated tertiary reserve allocation, is designed to optimize the dispatch of distributed energy resources and to provide load balancing in a local power distribution network. Dispatch optimization can include economical, technical, and environmental optimization [64]–[66]. In a microgrid with a mix of renewable resources and fossil fuel power generation, the control system improves the management of DG units, energy storage, and associated loads, e.g., by attaining an optimal dispatch that increases the renewable energy utilization while reducing the fossil fuel consumption. In this way, the tertiary level of control is related to the usage of an EMS, such as the EMS for ensuring a stable operation in an islanded microgrid and minimizing the fuel consumption in [64]. The tertiary controller can coordinate the power flow within the microgrid, by using an optimal power flow solver. In [59], [67], an overview of such solvers is given with solvers focusing on the allocation and optimal power sharing of the DG units, often solar or wind, and others highlighting the economic revenue. An optimum power solver with integration of an energy storage device to compute its optimal energy management is discussed in [59].

The optimization process is done in two levels.

1) *Power flow optimization*: reactive power can be optimized in real-time to achieve optimum power flow. Active power also can be optimized, but it is more related to energy if considered along the day.
2) *Energy optimization*: one day ahead, the energy can be optimized according to the generation and load forecasts. Forecasting in small-scale microgrids is hard, but a sub-optimal solution can be found corresponding to an objective cost function that contains economical information that would be related to energy costs, CO_2 emissions, and efficiency, among others.

In [17], [68], and [69], it is suggested that three control levels are present in a grid-connected microgrid, i.e., 1) local microsource controllers (MCs) and load controllers (LCs), 2) microgrid system central controller (MGCC), and 3) distribution management system (DMS). The latter to relate to the tertiary control. The MGCC is responsible for the maximization of the microgrid value and the optimization of the microgrid during operation, i.e., optimizing the production of the local DG units and the power exchanges with the main distribution grid (DMS). Different MAS philosophies, market policies, and bidding options have been considered [69], [70].

Microgrids can supply ancillary services that can be used for the primary reserve provision.

Discussion

Distribution networks (medium voltage) are increasingly being confronted with congestion problems. Also, the traditional planning rules for allowing new DG units in the system, based on worst-case scenarios of maximum generation together with minimum loads, significantly limit the hosting capacity for DG. Therefore, there is a trend toward smarter planning rules where smart control may curtail DG units when necessary. For example, for wind turbines, this curtailment can be done by a central controller, i.e., in a tertiary control scheme sending set-point commands [71].

Managing the instantaneous active and reactive power balances inside a microgrid and possibly also the exchange with the utility network becomes difficult while maintaining proper network voltage profiles because the high resistance to reactance ratio of low-voltage networks leads to the coupling of real and reactive power. This goes against the technically acceptable state of decoupled active and reactive power during operation. Therefore, the hierarchical control in power quality issues should be carefully dealt with and matched to network standards, which aids to identify the availability of network running states.

While the benefits of hierarchical control applied to microgrids have been explored, there is abundant literature about the technical challenges and regulatory issues that should be considered. In addition to this, international case studies illustrate that financial and stakeholder challenges also need to be addressed before microgrids can be smoothly implemented, such as handling the transition from island to grid-connected mode of operation or vice versa by using secondary control for synchronization issues, either intentionally or due to a fault event, and particularly to have enough generation to provide high power quality. Also, the ability to achieve a black start transition is relevant in case seamless transitioning fails.

Finally, most current research on barriers to microgrid implementation focuses on technical challenges during microgrid operation, and recently, some dedicated research has begun identifying the regulatory and market barriers. Additionally, more research should be done on how to optimally engage end-users to understand the enabling terms and conditions established by the DSO as well as how the market mechanism functions to trade power.

Conclusion

This article discussed the hierarchical control of islanded microgrids. Concerning the local primary control, the DG units can be classified into the grid-following or grid-forming units. In islanded microgrids, at least one grid-forming unit is required. To enable power sharing between multiple units after a load variation, the grid-forming droop controllers have been developed. In this way, the primary control of the microgrid is fully distributed. Possible means for the primary reserve (grid-following and grid-forming) and preprimary reserve have been discussed.

For the secondary control, a centralized MGCC is often used for the voltage and frequency set-point retrieval as well as for modifying the power sharing by taking into account the line impedance. The tertiary control is implemented in a centralized control scheme, e.g., for economic optimization or communication with the distribution network operator to provide ancillary services. The secondary and tertiary controllers modify the set points of the primary control schemes.

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