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

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Published in:
I E E E Industrial Electronics Magazine

DOI (link to publication from Publisher):
10.1109/MIE.2013.2279306

Publication date:
2013

Document Version
Early version, also known as pre-print

This document is a preprint version of the paper T.L. Vandoorn, J.M. Guerrero, J.D.M. De Kooning, J. Vasquez, and L. Vandevelde, "Decentralized and centralized control of islanded microgrid including reserve management," IEEE Industrial Electronics Magazine, 2013.

Decentralized and centralized control of islanded microgrids including reserve management

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Abstract - The increasing share of distributed generation (DG) units in the 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 for a coordinated approach for integrating DG in the network, allowing the DG units to actively contribute in the frequency and voltage regulation. Microgrids can provide such coordination by aggregating DG, (controllable) loads and storage in small-scale networks, that can operate both in grid-connected and islanded mode. Here, the islanded operating condition is considered. Analogous 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 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.

Index terms - Distributed Generation, Droop Control, Microgrid, Hierarchical Control

I. Introduction

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

Concerning the grid control, islanded microgrids have specific characteristics that differ significantly from those of the traditional power system. Firstly, 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. Secondly, 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. Thirdly, 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

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The work of T. Vandoorn is financially supported by a Fellowship of the FWO-Vlaanderen (Research Foundation - Flanders, Belgium). This research has been carried out in the frame of the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office (IAP-VII-02). The research of J. D. M. De Kooning is funded by the Special Research Fund (BOF) of Ghent University (Belgium)

control. Hence, for the primary control in microgrids, new control concepts have been developed [1], [3]–[8].

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 with the conventional grid control. Hence, it is based on local measurements only, 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. 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 inter-unit 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 grid-following and grid-forming reserve by the droop controlled DG units. 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 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. In this context, the provision of pre-primary and primary reserve by the grid elements, i.e., generators, loads and storage elements, is discussed. Further, the grid elements' primary responses are classified in grid-forming and grid-following reserve provision.

Hierarchical control for microgrids and especially the reserve provision related to this have been proposed recently in order to standardize the microgrid operation and functions [9], [10]. Three main control levels have been defined in such a hierarchy, i.e., primary, secondary and tertiary control. Fig. 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 below.

In order to achieve global controllability of the microgrid, 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 in order 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 in order 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]. Further, other objectives regarding voltage control and power quality, such as voltage unbalance and harmonic compensation by means of the secondary controller, have been proposed recently [14]. Although secondary control systems conventionally have been implemented in a centralized manner in the MGCC, distributed control strategies can be implemented as well [15]. A multi-agent system (MAS) can be applied, e.g., 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. A method for increasing the accuracy of the reactive power-sharing scheme has been presented in [18], which introduces an integral control of the load bus voltage, combined with a reference that is drooped against the 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 conventional frequency droop control and by using communication [19]. Opposed to the primary control, which needs to be designed specifically for application in islanded microgrids, secondary and tertiary controllers are generally based on similar controllers used in the (smart grid) power system and in energy management systems 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]. When connected to the grid, this control level takes care not only of the energy and power flows, but also of the power quality at the point of common coupling (PCC). Furthermore, the centralized tertiary controller exchanges information with the distribution system operator (DSO) in order to optimize the microgrid operation within the utility grid.

This article analyzes the hierarchical control in a microgrid and the reserve allocation in this context. Reserves are usually classified in primary and secondary reserves [20]. In the 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 seconds and the secondary reserves reset the primary control reserves in 5-15 minutes. 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 grid-forming and grid-following reserve. This distinction is mainly dependent on the order they are committed. The grid-forming reserve is allocated primarily, e.g., by the dispatchable units. The grid-following reserve is allocated secondly when the grid-forming reserve is not sufficient anymore. 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, pre-primary reserve needs to be provided. The pre-primary 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.

This article is organized as follows. In section II, the local primary control of islanded microgrids, i.e., droop control, is discussed. Primary control is, mostly, decentralized as it locally deals with the DG units and avoids inter-unit communication for reliability reasons. In this context, the primary and pre-primary reserve provision in accordance with these droop controllers is highlighted. The primary reserve is classified as grid-forming or grid-following reserve. Section III deals with secondary and tertiary controls. Tertiary control is centralized, since it is concerned with the global microgrid optimization, e.g., power flow optimization in the microgrid. Secondary control systems have been implemented conventionally in the MGCC, thus, in a centralized control scheme.

II. Local control

The control of uninterruptible power supplies (UPSs) can be regarded as the starting point for islanded microgrid control. Like in microgrids, 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. The most striking difference however, 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, opposed to UPS control, which is often based on master/slave and centralized control [21]. The reason is twofold. Firstly, building a new communication infrastructure for primary control can be uneconomical. Secondly, and more importantly, a communication link induces a possible single point of failure that can affect the reliability of the system. 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.

For the local primary control without inter-unit communication, the units can be classified in either grid-following or grid-forming. 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 not changed 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 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. 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. Such kind of primary reserve, called grid-forming reserve, can also be implemented in storage units.

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

A. 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 predefined reference voltage to a single network. This would lead to synchronization problems, circulating currents and inaccurate power sharing (i.e., a power delivery which 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 can enable stand-alone operation. The primary grid-forming reserve is available as long as the battery storage or available diesel remains sufficient. Generally, primary grid-following reserve is not yet available in practice. However, new grid-following DG units are sometimes already equipped with primary grid-following reserve. An example is the frequency response in grid-following PV inverters. The grid-forming 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 Fig. 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 rose above 50.2 Hz, the converters (PV) had to shut down. Starting from 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.

B. 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 inter-unit communication. Droop control in microgrids mimics the conventional grid control which is based on the well-known P/f and Q/V droop controllers in Fig. 3(b). In the conventional network, the large synchronous generators 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 upon 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, Fig. 3(a), 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 (Fig. 3(b)).

1) 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. In order 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], hybrid droop controllers [27] and modified droop controllers [28].

2) Primary reserve: The assignment of 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 grid-forming reserve may include battery storage or flywheel energy storage, an example of which is given in [29].

Renewables are not considered as grid-forming units, hence they only provide grid-following reserve. Concerning the grid-following reserve, several potential solutions are discussed below. 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 depending on the frequency to provide primary reserve [32]. However, deterministic control schemes prove to be inadequate as the consumption of different individual appliances tends to synchronize. Therefore, in [33], decentralized random controllers are used for 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.

3) Pre-primary 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 virtual synchronous generators (VSGs), to damp initial transients and stabilize the system.

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

$$P^\star_{\mathrm{VSG}} = -J_{\mathrm{VSG}}\hat{\omega}\frac{\mathrm{d}\hat{\omega}}{\mathrm{dt}}, \tag{1}$$

with J_{VSG} the virtual moment of inertia; the pulsation $\hat{\omega}$ and $\frac{\mathrm{d}\hat{\omega}}{\mathrm{dt}}$ are estimated by 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. Eq. (1) determines the additional $P^\star_{\mathrm{VSG}}$ exchange with this storage element. The total power is determined according to:

$$P_{\mathrm{tot}} = P_{\mathrm{ref}} + P^\star_{\mathrm{VSG}} + P^\star_{\mathrm{droop}}. \tag{2}$$

$P^\star_{\mathrm{droop}}$ 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 on the situation. In synchronverters, which are similar to VSGs, the electrical and mechanical models of a synchronous generator (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].

b) 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]:

$$P_{\mathrm{in}} - \hat{P}_{\mathrm{out}} = J\omega^\star_n\frac{\mathrm{d}\omega^\star_n}{\mathrm{dt}} - Ds, \tag{3}$$

with D damping factor, J inertia moment, ω_n angular velocity of virtual rotor, s slip, $s = \omega_{\mathrm{n,0}}\Delta\omega^\star_n$ with $\omega_{\mathrm{n,0}}$ 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 fo 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. Eq. (3) is used to determine $\omega_n^\star$, from which the inverter's phase angle $\theta^\star$ is calculated. The reference voltage is calculated by 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, 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 a synchronous generator in a VSG based on power measurements.

c) Other methods: Instead of using an additional storage element for the pre-primary reserve, other methods exist that can be included in the loads, storage and generators as well. A first example is a wind turbine with an additional pre-primary reserve support function in [43], also called inertial response of wind turbines. This wind turbine is controlled in order 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. Secondly, 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. Also, a frequency gradient is included.

C. 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. Low-voltage lines typically have a high R/X value [44]. In predominantly resistive networks, Fig. 4(a), 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 Fig. 4(b) [45].

1) 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 to share 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]. Hence, it steers towards the usage of P/f droops or towards the implementation of more virtual resistance in the DG units.

Similar with the Q/V droops in the conventional grid control, there is a trade-off 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 § III-C.

Another variant of the traditional P/V droop control is the voltage-based droop (VBD) control shown in Fig. 6(a) [7]. For the active power control, this droop controller consists of a combination of a $V_{\text{g}}/V_{\text{dc}}$ 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 constant-power band) to more extreme voltages (Fig. 5(b)).

Table I and Fig. 6 show some measurement results of the VBD controller. The measured DG unit terminal voltage of case 7 is depicted in Fig. 6(a) and the accuracy of the voltage tracking is illustrated in Fig. 6(b). The microgrid test set-up consists of two DG units connected to a load. The load consists of either a 13 or 27 Ω load. The inverters of the DG units

TABLE I

MEASUREMENT RESULTS 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	2.8	2	180.8	141.0	471
		2	∞	1	1	169.9	119.9	160
5	13	1	0	2.5	2	186.3	146.5	445
		2	∞	1.5	1.5	181.3	144.4	266
6	27	1	0	1.5	2	212.9	173.2	300
		2	∞	1	1	212.1	172.3	206
7	13	1	0	3.5	4	205.9	166.2	686.5
		2	∞	1	1	189.5	149.7	180.9

have been realized by using a printed circuit board (PCB) that was developed in Ghent University. The switches consist of 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 μF. 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 $I_{\mathrm{dc}}/V_{\mathrm{g}}$ 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, $V_{\mathrm{g,nom}} = 160$ V, the droop of the $I_{\mathrm{dc}}/V_{\mathrm{g}}$ droop controller equals -0.04 A/V and the droop of the $V_{\mathrm{g}}/V_{\mathrm{dc}}$ 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 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 $V_{\mathrm{g}}/V_{\mathrm{dc}}$ droop controller. For, e.g., 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, DG 1 is dispatchable, while DG 2 remains with large constant-power band. Hence, $I_{\mathrm{dc,1}}$ is determined by the $I_{\mathrm{dc}}/V_{\mathrm{g}}$ droop controller and $I_{\mathrm{dc,2}}$ is still solely determined by the primary energy source. When comparing cases 4 and 6, indeed DG 1 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 DG 1 doubles in case 7, i.e., $I_{\mathrm{dc,1,nom}} = 4$ 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.

2) 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 frequency to grid voltage. The VBD 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) dispatchable DG units, 2) assigned storage, 3) highly controllable loads, 4) less dispatchable DG units (including local storage, maximum power point changes, and local load changes), 5) less controllable loads. To what group a specific grid element is assigned can vary in time dependent on the constraints of the unit. The usage of VBD control with constant-power bands, enables that the local network state is 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, loads shift their consumption towards high-voltage times [48] as shown in Fig. 7.

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

D. Discussion

Primary control reserve is crucial in the network exploitation, now and even more in the future networks, and both in 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. Due to 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 in this paragraph, 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 primary reserve is by including this into the market. However, most DG units currently are too small to participate in the markets, hence, cannot benefit from 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 local control strategies. 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 are increasingly being confronted with balancing (reserve) and congestion problems.

III. 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. Fig. 8 shows a microgrid hierarchical control architecture. It consists of a number of 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 in order 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. Distributed secondary control addresses this issue [15]. Every DG unit has its own local secondary controller which can produce appropriate control signal for the primary control level by using the measurements of other DG units, e.g,. in order 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 a MGCC is mandatory to achieve some other purposes like coordination of the MG units in black start process or energy management.

In summary, 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 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 systems (NCS) [54], [55].

A. Frequency control

Traditionally, in large power systems, 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 USA, is based on a slow 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 in order to restore the frequency of a microgrid consisting of P/f droop controlled DG units or the aforementioned variations such as VSGs [53].

B. 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 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. Voltage unbalance compensation and harmonics mitigation can be dealt with by a local controller [56]. Also, 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 point of common coupling [58]. These secondary controllers send proper control signals to the DG units' local controllers.

C. 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 P/V - Q/f droop controllers. Several solutions to increase the power sharing accuracy have been presented in literature. Firstly, 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]. In order 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]. Secondly, 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, firstly, the conventional Q/V droops and, secondly, 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 in order to be averaged and sent back to each unit as a Q reference from the droop control [62].

D. 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, 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 a MGCC, which also receives information from the Distributed Network Operator (DNO).

The most advanced country in the terms of including combined heat and power (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 Fig. 9. The TSO has organized the primary reserve market as a day-ahead market, split into six four-hour 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 and waste heat from industry and now is considering to invest in a large-scale heat pump.

E. 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 energy management systems (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, and this according to the generation and load forecasts. Forecasting in small scale microgrids is hard, but a suboptimal solution can be found corresponding to an objective cost function that contains economical information that would be related to energy costs, CO_2 emissions, efficiency, among others.

In [17], [68], [69], it is suggested that three control levels are present in a grid-connected microgrid, i.e., (1) local microsource controllers (MC) and load controllers (LC), (2) microgrid system central controller (MGCC) and (3) distribution management system (DMS). 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 multi-agent system (MAS) philosophies, market policies and bidding options have been considered [69], [70].

F. 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 towards 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, 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 in order to understand the enabling terms and conditions established by the DSO as well as how the market mechanism functions to trade power.

IV. Conclusion

This article discusses the hierarchical control of islanded microgrids. Concerning the local primary control, the DG units can be classified in 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, grid-forming droop controllers have been developed. In this way, the primary control of the microgrid is fully distributed. Possible means for primary reserve (grid-following and grid-forming) and pre-primary reserve have been discussed.

For the secondary control, often a centralized MGCC is used, for the voltage and frequency set-point retrieval as well as for modifying the power sharing by taking into account the line impedance. 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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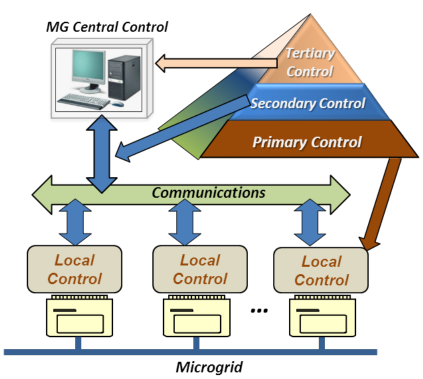


Fig. 1. MicroGrid communications, local and centralized controllers

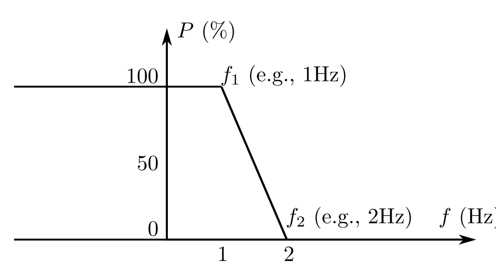
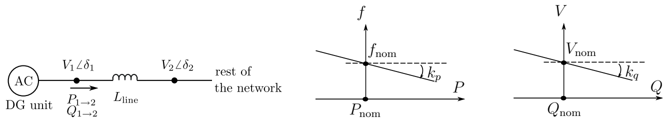


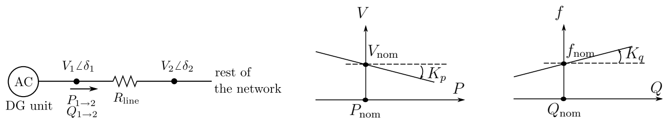
Fig. 2. Grid-following inverter with P/f characteristic



(a) P-f linkage Q-V linkage in inductive networks

(b) P-f and Q-V droop controllers

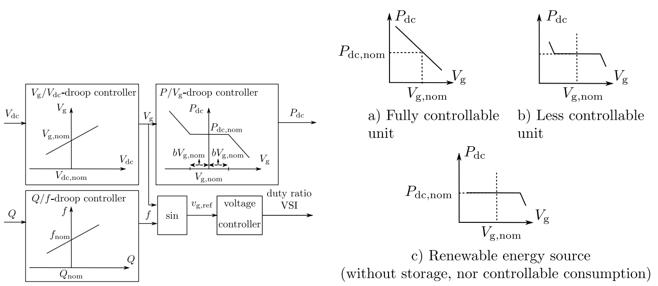
Fig. 3. P/f droop control



(a) P-V linkage Q-f linkage in resistive networks

(b) P-V and Q-f droop controllers

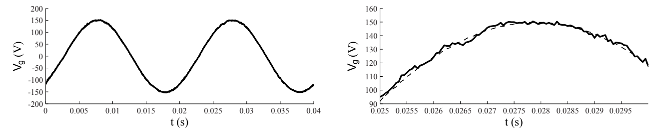
Fig. 4. P/V droop control



(a) Control strategy

(b) Constant power bands of dispatchable versus less-dispatchable DG units

Fig. 5. Voltage-based droop control



(a) Voltage profile

(b) Voltage tracking

Fig. 6. Voltage tracking results in a two-DG unit microgrid with VBD control

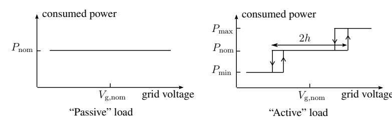


Fig. 7. Grid-following reserve in the loads

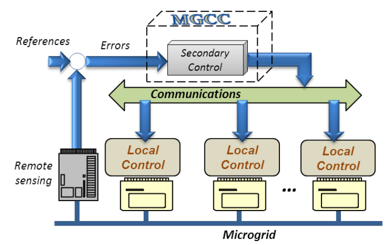


Fig. 8. Centralized secondary controller

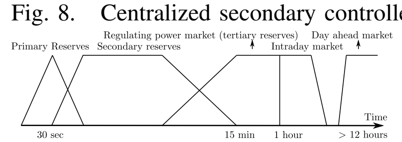


Fig. 9. Overview of the Danish electricity markets