Microgrid controls

Bevrani H

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16.9 MICROGRID CONTROLS

BY H. BEVRANI, M. WATANABE, AND Y. MITANI

Currently, economical harvesting of electrical energy on a large scale considering the environmental issues is undoubtedly one of the main challenges. As a solution, microgrids (MGs) promise to facilitate the wide penetration of renewable energy sources (RESs) and energy storage devices into the power systems, reduce system losses, and greenhouse gas emissions, and increase the reliability of the electricity supply to the customers. Due to their potential benefits to provide secure, reliable, efficient, sustainable, and environmentally friendly electricity from RESs, the interest on MGs is growing.

Although the concept of MG is already established, the control strategies and energy management systems for MGs which cover power interchange, system stability, frequency and voltage regulation, active and reactive power control, islanding detection, grid synchronization, and system recovery are still under development. In this research, a comprehensive review on various MG control loops and the relevant standards are given with a discussion on challenges of MG controls.

16.9.1 Microgrids

A microgrid (MG) is an interconnection of domestic distributed loads and low-voltage distributed energy sources, such as microturbines, wind turbines, PVs, and storage devices. The MGs are placed in the low-voltage (LV) and medium-voltage (MV) distribution networks. This has important consequences. With numerous microsources connected at the distribution level, there are new challenges, such as system stability, power quality and network operation that must be resolved applying the advanced control techniques at LV/MV levels rather than high voltage levels which is common in conventional power system control. In other words, distribution networks (demand side) must pass from a passive role to an active one.

A simplified MG architecture is shown in Fig. 16-66. This MG consists of a group of radial feeders as a part of a distribution system. The domestic load can be divided to sensitive/critical and nonsensitive/noncritical loads via separate feeders. The sensitive loads must be always supplied by one or more microsources, while the nonsensitive loads may be shut down in case of contingency, or a serious disturbance.

Each unit's feeder has a circuit breaker and a power flow controller commanded by the central controller or energy manager. The circuit breaker is used to disconnect the correspondent feeder (and associated unit) to avoid the impacts of severe disturbances through the MG. The MG is connected to the distribution system by a point of common coupling (PCC) via a static switch (SS in Fig. 16-66). The static switch is capable to island the MG for maintenance purposes or when a fault or contingency occurs. All such events are well described in the standard IEEE 1547.[1]

For the feeders with sensitive loads, local power supply, such as diesel generators or energy capacitor systems (ECSs) with enough energy saving capacity are needed to avoid interruptions of electrical supply. The MG central controller (MGCC)[2] facilitates a high-level management of the MG operation by means of technical and economical functions. The microsource controllers (MCs) control the microsources and the energy storage systems. Finally, the controllable loads are controlled by load controllers (LC).

The microsources and storage devices use power electronic circuits to connect to the MG. Usually, these interfaces depending to the type of unit and connected feeder are ac/ac, dc/ac, and ac/dc power

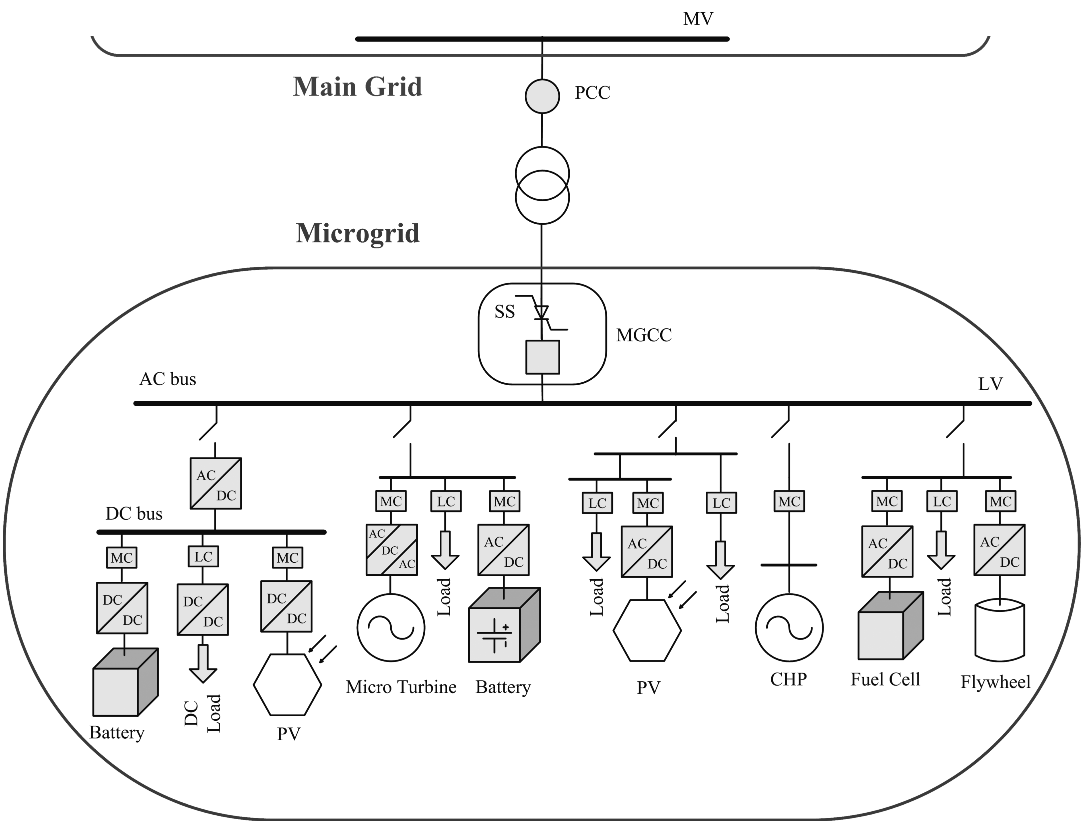

FIGURE 16-66 Simplified MG structure.

electronic converters/inverters. As the MG elements are mainly power-electronically interfaced, the MG control depends on the inverter control.

There are a variety of modulation techniques that can be used in power electronic inverters/converters including pulse width modulation (PWM), hysteresis modulation, and pulse density modulation (PDM). Hysteresis modulation is perhaps the simplest, but due to some shortcomings to provide high quality output current and good transient response, it is not preferred for MG inverters. PWM is the most common modulation technique in the MG's inverters/converters. The PDM technique is another possible modulation technique, which is used in high frequency converters applied for induction heating applications.

Generally, the inverters have two separate operation modes, acting as a current source or as a voltage source. The general model for an inverter-based microsource is shown in Fig. 16-67. A microsource contains three basic elements: power source or prime mover, dc interface, and inverter. The microsource couples to the MG through a power line. The output voltage and frequency, as well as real and reactive powers of the microsource can be controlled using local feedbacks applied to the inverter.

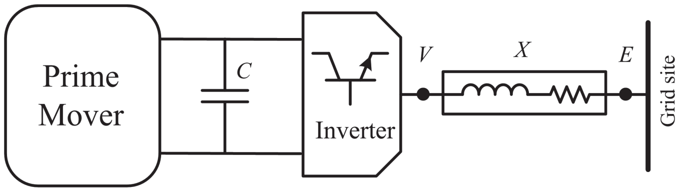

FIGURE 16-67 A model for a microsource connected to a MG.

In comparison to the conventional generators, the microsources (DGs) such as natural gas and diesel generating units are very fast and can typically pick up load within 10 to 12 s from start-up and can serve full load just a few seconds thereafter. The microsource can control the phase and magnitude of its output voltage *V* and from the line reactance *X*, it can determine the transferring real power *P*, and reactive power *Q* flows from itself to the grid. *P* and *Q* values can be calculated as follows:

$$P = \frac{3}{2}\frac{VE}{X}\sin\delta \tag{16-22}$$

$$P = \frac{3}{2}\frac{V}{X}(V - E\cos)(\delta) \tag{16-23}$$

where

$$\delta = \delta_V - \delta_E \tag{16-24}$$

The *E* is the voltage at grid side of the connecting line; the δ_v and δ_E are the angles of *V* and *E*, respectively. For small δ, *P* and *Q* mainly depend on δ and *V*, respectively:

$$P \approx \frac{3}{2}\frac{VE}{X}\,\delta \tag{16-25}$$

$$P \approx \frac{3}{2}\frac{V}{X}\,[(V - E)\delta] \tag{16-26}$$

The above relationships allow us to establish feedback loops in order to control output power and MG voltage in islanding.

The above relationships show if the reactive power in the MG generated by the microsources increases, the local voltage must decrease, and vice versa. Also, there is similar behavior for frequency versus real power. These relationships that are formulated in Eqs. (16-27) and (16-28) which allow us to establish feedback loops in order to control MG's real/reactive power and frequency/voltage.

$$\omega - \omega_0 = -R_P(P - P_0) \tag{16-27}$$

$$V - V_0 = -R_Q(Q - Q_0) \tag{16-28}$$

ω_0, P_0, V_0, and Q_0 are the nominal values (references) of frequency, active power, voltage and reactive power, respectively. A graphical representation for Eqs. (16-27) and (16-28) is shown in Fig. 16-68.

The interconnected DG units with different droop characteristics can jointly track the load change to restore the nominal system frequency and voltage. This is illustrated in Fig. 16-68, representing two units with different droop characteristics connected to a common load. The DGs are operating at a unique nominal frequency/voltage with different output active/reactive powers. The change in the network load causes the microsources to decrease their speed/voltage, and hence, the units increase the output powers until they reach a new common operating frequency/voltage. As expressed in Eq. (16-29), the amount of produced power by each DG to compensate the network load change depends on the unit's droop characteristics.[3]

$$\Delta P_{gi} = \frac{\Delta\omega}{R_{Pi}}, \Delta Q_{gi} = \frac{\Delta V}{R_{Qi}} \tag{16-29}$$

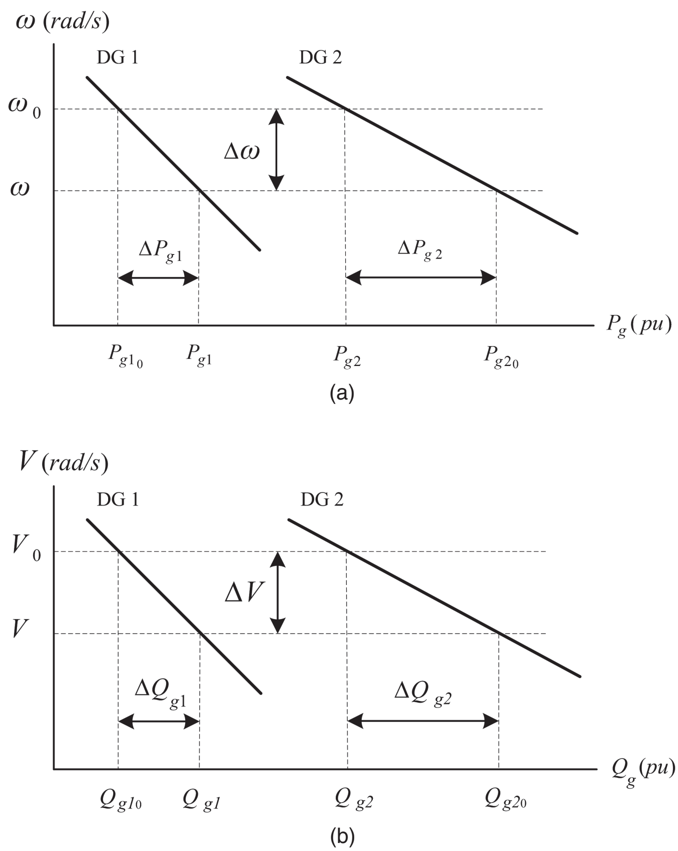

FIGURE 16-68 Droop control characteristics: (*a*) $\omega - P$ droop, (*b*) $V - Q$ droop.

Hence,

$$\frac{\Delta P_{g1}}{\Delta P_{g2}} = \frac{R_{P2}}{R_{P1}} \tag{16-30}$$

and

$$\frac{\Delta Q_{g1}}{\Delta Q_{g2}} = \frac{R_{Q2}}{R_{Q1}} \tag{16-31}$$

It is noteworthy that the described droop controls characteristics in Eqs. (16-27), (16-28), and Fig. 16-68 have been obtained for electrical grids with inductive impedance ($X >> R$) and great amount of inertia, which is the case in conventional power system with high-voltage lines. In a conventional power system, immediately following a power imbalance due to a disturbance, the power is going to be balanced by natural response generators using rotating inertia in the system via the primary frequency control loop.[4] In the MG on the other hand, there is no significant inertia and if an unbalance occurs between the generated power and the absorbed power, the voltages of the power sources change. Therefore, in this case, voltage is triggered by the power changes.

In fact, for medium and low-voltage lines, which the MGs are working with, the impedance is not dominantly inductive ($X \cong R$). For resistive lines, reactive power Q mainly depends on δ and real power P depends on voltage V.[5] This fact suggests different droop control characteristics, called opposite droops. Recently, several researches have been done to introduce new and specific droop characteristics for the MG control design purposes.

However, each micro generator has a reference reactive power to obtain a voltage profile, which matches the desirable real power. In low-voltage grids, Q is a function of δ, which is adjusted with the V versus P droop. It means there is possibility to vary the voltage of generators exchanging the reactive power.[6,7] So, the conventional droops are still operable in low voltage grids and MGs.

In a grid-connected operation, MG loads receive power from both the grid and local microsources, depending on the customer's situation. In emergency conditions, for example, following a problem for the main grid (such as voltage drops, faults, blackouts), the MG can be separated from the grid via a static switch in about a cycle, as smoothly as possible. The MG can be also islanded intentionally for specific reasons even though there is no disturbance or serious fault in the main grid side. In these cases, the MG operation is continuing in islanding operation mode.

The balance between generation and demand of power is one of the most important requirements of MG management in both grid-connected and islanded operation modes. In the grid-connected mode, the MG exchanges power to an interconnected grid to meet the balance, while, in the islanded mode, the MG should meet the balance for the local supply and demand using the decrease in generation or load shedding.

During the grid-connected mode, the generating units operate in current-control mode, in which they should regulate the exchange of active and reactive powers between the MG and the main grid. While during islanded operation, the DGs operate in voltage-control mode to regulate the MG voltage and to share the local loads. In islanding, if there are local load changes, local microsources will either increase or reduce their production to keep constant the energy balance, as far as possible. In an islanded operation, a MG works autonomously, therefore must have enough local generation to supply demands, at least to meet the sensitive loads. That is not the case in grid-connected operation, because in this situation, the main grid compensates the increases or decreases of the load.

Therefore, islanding operation could be happen under two scenarios: planned (intentional) and unplanned (unintentional) islanded operations. Planned islanded operation can be done for maintenance purposes, economical criterion, or in case of a long-term voltage dips or general faults following an event in the main grid. Unplanned islanded operation may happen following a contingency such as severe disturbance (or blackout) in the main grid.

Immediately after islanding, the voltage, phase angle and frequency at each microsource in the MG change. For example, the local frequency will decrease if the MG imports power from the main grid in grid-connected operation, but will increase if the MG exports power to the main grid in the grid-connected operation.

16.9.2 Control in Microgrids

The main profits associated to the MG concept can be considered as efficiency improvement in energy transmission, considerable reduction environmental pollution (e.g., emissions of CO_2 and SO_2), and security/reliability enhancement, considering the inherent redundancy of DGs. But the high penetration of DGs certainly increases the complexity of control, protection, and communication of distribution systems, which are namely designed to operate radially without any generation at the low voltage distribution lines or customer side. An important issue is how to integrate the numerous MGs into existing distribution networks by properly coordinating their generator/storage units operation and by limiting their potentially negative side effects on network operation and control.

Control is one of the key enabling technologies for the deployment of MG systems. The MG has a hierarchical control structure with different layers. The MGs require effective use of advanced control techniques at all levels. The secure operation of MGs in connected and islanding operation modes, as well as successful disconnection or reconnection processes depend upon MG controls. The controllers must guarantee that the processes occur seamlessly and the system is working in the specified operating points.

Due to high diversity in generation and loads, the MGs exhibit high nonlinearities, changing dynamics, and uncertainties that may require advanced robust/intelligent control strategies to solve. The use of more efficient control strategies would increase the performance of these systems. Since, some RESs such as wind turbines and PVs are working under turbulent and unpredictable environmental conditions, the MGs have to adapt to these variations and in this way the efficiency and reliability of MGs strongly depend on the applied control strategies.

As already mentioned, the MGs should be able to operate autonomously but also interact with the main grid. In connected operation mode, the MGs are integrated to a constantly varying electrical grid with changing tie-line flow, voltages, and frequency. To cope to those variations, and to response to grid disturbances; and performing active power/frequency regulation, and reactive power/voltage regulation, the MGs need to use proper control loops. Furthermore, suitable islanding detection feedbacks/algorithms are needed for ensuring a smooth transition from grid-connected to islanded mode to avoid cascaded failures.

In islanded mode, the MG operates according to the existing standards (e.g., IEEE 1547) and the existing controls must properly work to supply the required active and reactive powers as well as to provide voltage and frequency stability. A controlled switch reconnects the MG to the grid when the grid voltage is within acceptable limits and the phasing is correct. In this stage, active synchronization is required to match the frequency, voltage, and phase angle of the MG.

A general scheme for operating controls in a MG is shown in Fig. 16-69. Each MG is locally controlled by the MCs. The LCs are installed at the controllable loads to provide load control capabilities. For each MG, there is a central controller (MGCC) that interfaces between the distribution management system (DMS) or distribution network operator (DNO) and the MG. The DMS/DNO has responsibility to manage the operation of medium and low voltage areas in which more than one MG may exist. Later, these controllers are explained in detail.

Similar to the conventional power systems,[8] the MGs can operates using various control loops which can be mainly classified in four control groups: local, supplementary, global and emergency controls. The *local control* deals with initial primary control such as current and voltage control loops in the microsources. The *supplementary control* ensures that the frequency and average voltage deviation of the MG is regulated towards zero after every change in load or supply. It is also responsible for inside ancillary services. The *global control* allows MG operation at an economic optimum and organizes the relation between a MG and distribution network as well as other connected MGs. The *emergency control* covers all possible emergency control schemes and special protection plans to maintain the system stability and availability in the face of contingencies. The emergency controls identify proper preventive and corrective measures that mitigate the effects of critical contingencies.

In contrast to the local control, operating without communication, supplementary, global and emergency controls may need communication channels. While, the local controls are known as *decentralized* controllers, the global, and to some extent, supplementary and emergency controllers are operating as *centralized* controllers.

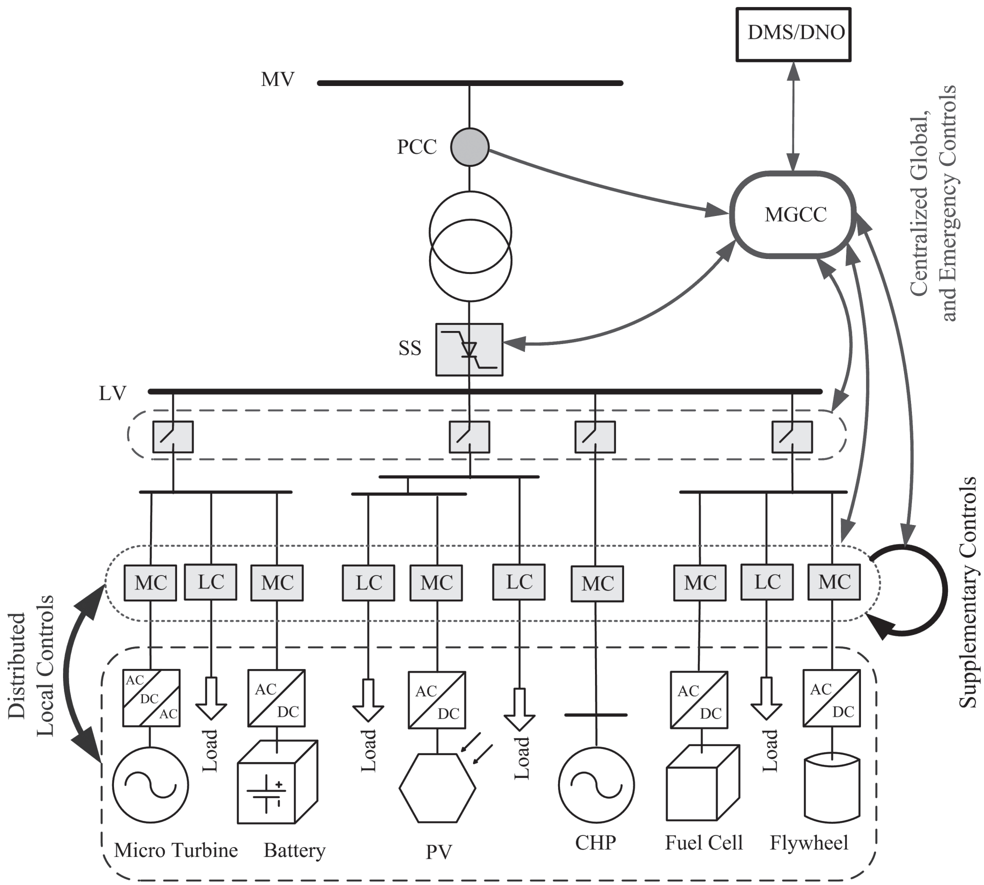

FIGURE 16-69 A general scheme for MG controls.

Figure 16-70 shows a conceptual framework for the described operating control loops in a MG. In summary, existing MG's control loops in four mentioned groups have the following responsibilities:

- Working of all microsources at the predefined operating points
- Interchanging active and reactive powers according to the scheduled plan
- Meeting the operating limits by all important electrical indices such as voltage and frequency among the MG
- Seamlessly islanding and resynchronizing processes using proper techniques
- Market participation optimizing
- Reducing the circulating currents among parallel connected microsources/inverters
- Guarantee secure power supply for sensitive loads
- Capability of operation through black start in case of general failure
- Providing emergency control and protective schemes such as load-shedding
- Possibility of remote operation of circuit breakers
- Proper using of energy storage devices

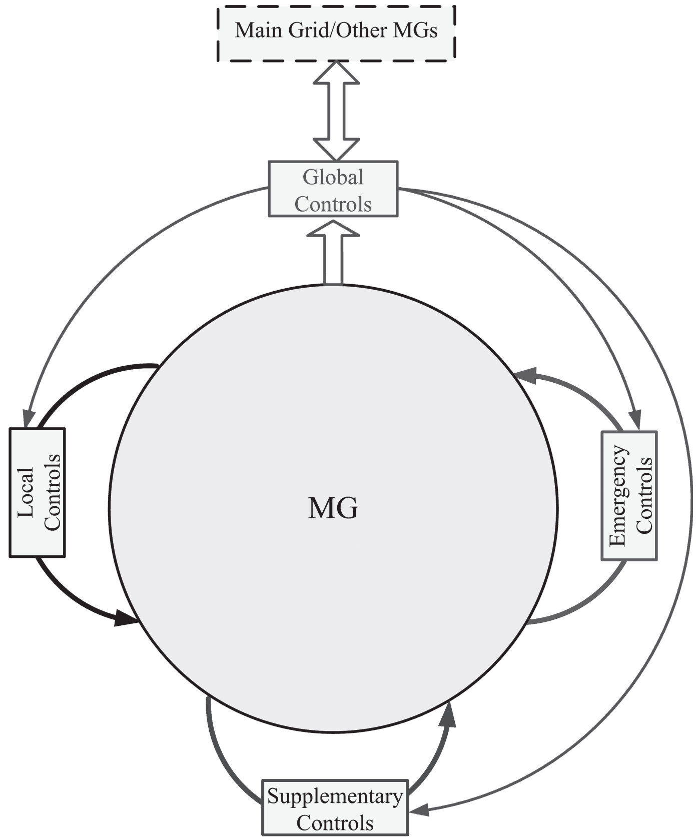

FIGURE 16-70 MG controls.

16.9.3 Local Controls

Local or internal controls are appeared in different forms depending on the type of microsources which can be addressed based on their technologies such as induction generators, synchronous generators, and power electronic Inverters/converters. Some microsources such as fuel cells and PV cells generate dc power, which for operation in an ac MG, must be connected to the network through dc/ac converters.

Older wind turbines and small hydro units use fixed speed induction generators (FSIG) that are connected directly to the grid. Modern variable speed wind turbines use doubly fed induction generators (DFIG) with their stators connected directly to the grid and their rotors connected via ac/dc-dc/ac converters. Some other power sources, such as combined heat and power (CHP) units, and micro turbines use synchronous generators. Synchronous generators operate at their synchronous speed if they are directly connected, similar to the control of large conventional generating units.

In FSIG wind turbines, the active power is merely determined by the mechanical power input, but reactive power and power factor can only be controlled with shunt compensators.[9] However, in the DFIG wind turbines, the rotor side converter controls the reactive power flow either for voltage or power factor control, and sets the rotor voltage and frequency for maximum power point tracking (MPPT). The grid side converter controls the power flow in order to maintain the dc-link capacitor voltage.[10]

In comparison of synchronous and induction generating units, the power electronic inverters/converters provide more flexible operation. The source-side inverter is usually a voltage source inverter (VSI) and is controlled to provide MPPT in wind turbine applications. The grid-side inverter in role of a line commutated inverter or a VSI controls the dc-link voltage to provide MPPT for PV or wind turbines with synchronous generators and diode rectifiers,[11] and also it can control the active and reactive power output.

The local controls deal with the inner control of the DG units that usually do not need the communication links result in simple circuitry and low cost. Local controls are the basic category of MG controls. The main usage of local controllers is to control microsources (Fig. 16-67) to operate in normal operation. This type of controllers is aimed to control operating points of the microsources and their power-electronic interfaces.

These controls are going to be more vital for a MG due to integration of large number of microsources in order to overcome fluctuation caused by high penetration of microsources. Some loads can be also locally controllable using the LCs. The LCs are usually used for demand side management.

For example, in solar plants the local controls are related to sun tracking and control of the thermal variables. Although control of the sun-tracking mechanisms is typically done in an open-loop mode, control of the thermal variables is mainly done in the closed loop mode. In microturbines and inverter-based energy sources such as wind turbines and uninterruptible power supply (UPS) based energy storage systems; it is the droop control, which ensures that the active and reactive powers are properly shared between the inverters. The local control loops are also responsible to regulate the unit output-voltage and limit the output current.

The main function of a DG in stand-alone and islanded mode is to assure the system stability and desirable performance by providing correct voltage and frequency in order to supply the local load. Figure 16-71 depicts a block diagram of local control loops for stand-alone inverter-based microsource. The outer loop regulates the output capacitor voltage v_0. After the addition with the measured output current, it sets the reference inductor current i^* for the inner control loop. Blocks PI-1 and PI-2 are the voltage and the current based proportional-integral (PI) regulators, respectively.

The voltage and frequency of the filter output voltage reference signal v_{ref} are kept constant, but their values could vary in case of working in the grid-connected operation mode, in this state, additional control, that is, v_{ref} droop control should be used.

Besides the voltage and frequency controls, microsources must control active and reactive powers. The droop-based active and reactive power controls are most common methods to control these powers. As described in Sec. 16.9.1, these droop controls are similar to the existing versions of droop-based controls in the conventional power systems. The droop-based control depicts the relation voltage and reactive power ($Q - V$), as well as frequency and active power ($P - \omega$) indices. Figure 16-72*a* shows a simple

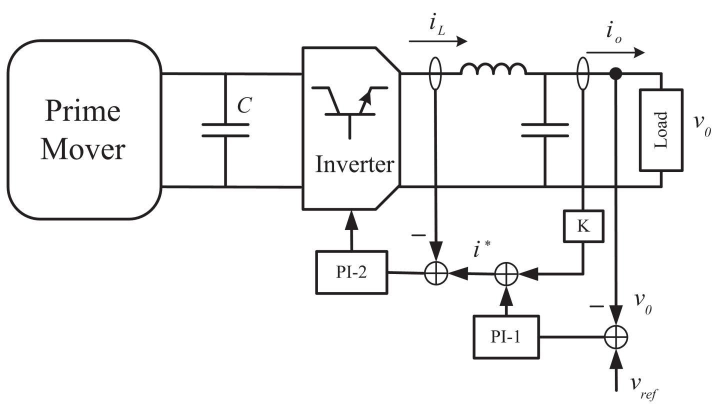

FIGURE 16-71 Local controls for a stand-alone inverter-based DG.

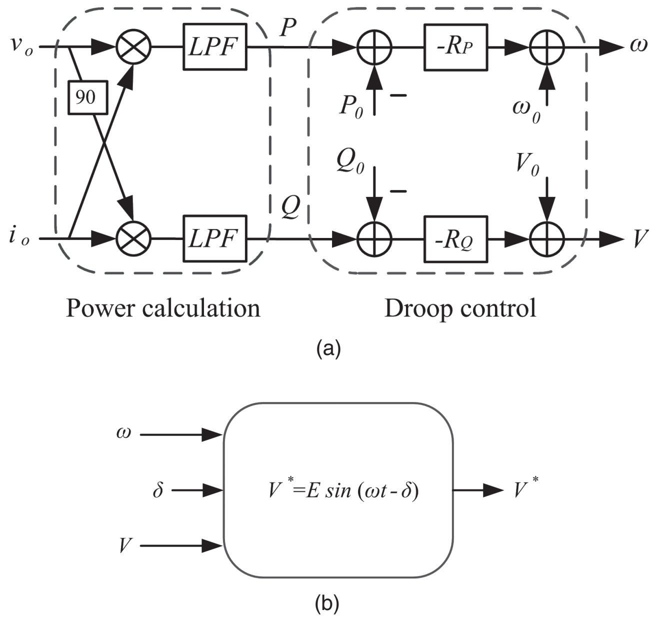

FIGURE 16-72 Realization of droop characteristics.

realization for droop-based control loops [Eqs. (16-27) and (16-28)] from output current and voltage measurements. As shown in Fig. 16-72*b*, the results can be used to provide the inverter voltage reference.

As the reactive power generated by the microsource increases (becomes more capacitive), the operating voltage increases, too. Therefore, the local voltage set-point should be reduced to keep the voltage at or near its nominal set-point. Same behavior exists for frequency and active power.

In the case of parallel inverters, these control loops, also called $P - \omega$ and $Q - E$ droops, use feedbacks from the voltage and frequency of each microsource/inverter for sensing the output average active and reactive powers to emulate virtual inertias. Therefore, in power electronic-based MGs, the droop control can be done by adding virtual inertias and controlling the output impedances; and can be useful to control active and reactive power injected to the grid. However, in the last case, the droop control is in face of several challenges that should be solved using advanced control methodologies. A slow transient response, line impedance dependency, and poor active/reactive power regulation are some of these challenges.

Synthesis of the local MG controllers is a crucial issue. The local controllers design should be based on a detailed dynamic model of the MG, including the resistive, reactive, and capacitive local load and the distribution system. This model should be adapted to the practical operating conditions of the MG in order to guarantee that the controllers respond properly to the system's inherent dynamics and transients.[12]

16.9.4 Supplementary Controls

Supplementary controls as second layer control loops complement the task of inner control loops to improve the power quality inside the MG and to enhance the system performance by removing the steady-state errors. They are closely working with local and global control groups.

During the grid-connected operation, all the microsources and inverters in the MG use the grid electrical signal as reference for voltage and frequency. However, in islanding, they lose that reference. In this case, they may coordinate to manage the simultaneously operation using one of following supplementary control methods: (1) Single master operation: a master microsource/inverter fixes voltage and frequency for the other units in the MG. The connected microsources are operating according to the reference given by the master. (2) Multimaster operation: in this case, several microsources/inverters are controlled by means of a central controller such as MGCC which chooses and transmits the set points to all the generating units in the MG.[13]

Supplementary controls also cover some of controls need to improve the parallel operation performance for DGs (or inverters). Sometimes, the commands provided by these controls are distributed through a low-bandwidth communication channels to the parallel DGs/inverters. There are many control techniques in the literature to make a successful parallel operation of DGs/inverters; they can be categorized into three main approaches:[14]

1. Master/slave control techniques, which use a voltage-controlled inverter as a master unit and current-controlled inverters as the slave units.[15] The master unit maintains the output voltage sinusoidal, and generates proper current commands for the slave units.
2. Current/power sharing control techniques, which by using them the total load current is measured and divided by the number of units in the system to obtain the average current. The actual current from each unit is measured and the difference from the average value is calculated to generate the control signal for the load sharing.
3. Generalized frequency and voltage droop control techniques, which use the normal conventional frequency/voltage droop control, opposite frequency/voltage droop control, or a combination of droop control with other methods.

Similar to the supplementary control in conventional power systems, supplementary controls in MGs are responsible to provide ancillary services. According to the IEEE Standard 1547,[1] the ancillary services in distributed power generation systems are defined as load regulation, energy losses, spinning and nonspinning reserve, voltage regulation, and reactive power supply. This standard recommends that low-power systems should be disconnected when the grid voltage is lower than 0.85 p.u. or higher than 1.1 p.u. as an anti-islanding requirement.[1,16]

In the MGs, because of variable nature of some renewable energy systems, such as photovoltaic (*PV*) or wind energy, and difficulty to predict the amount of produced power, the peaks of power demand may not necessarily coincide with the generation peaks. On the other hand, a network of small-size microsources that are dominated by power electronic-interfaced sources do not have enough inertia to response to the initial and surge power or energy mismatch by using their machines' inertia as commonly found in conventional power systems.

To solve this problem, storage energy systems such as flow batteries, fuel cells, flywheels, and superconductor inductors are used to supply the local loads, uninterruptible manner. These storage devices could be also useful to support regulation tasks and ancillary services in coordination with the MG's DGs. Coordination of storage devices and DGs for providing ancillary services to improve the system performance can be considered as a supplementary control. The capacity of the energy capacitor systems (ECS) depends upon the characteristics of regulation being provided.

An experimental control design example for using of ECS in a multiagent system (MAS) based coordination with a diesel generator for the load-frequency control (LFC) as a supplementary control issue is described in Ref. 17. The MG is considered as an isolated grid with dispersed microsources such as photovoltaic units, wind generation units, diesel generation units, and an ECS for the energy storage. The addressed scheme has been proposed through the coordination of controllable power microsources such as diesel units and the ECS with small capacity. All the required information for the proposed frequency control is transferred between the diesel units and the ECS through computer networks. The applied control structure is shown in Fig. 16-73. In this figure, W_{ECS} and P_{ECS} are the current stored energy and the produced power by ECS unit, respectively.

Here, ΔP_{ECS} and ΔP_{DG} represent the control action signals for output setting of ECS and diesel unit, respectively. Applying the control signal ΔP_{ECS} provides an appropriate charging/discharging operation on the ECS for the frequency regulation purpose. Because of specific feature of the ECS dynamics, the fast charging/discharging operation is possible to achieve in an ECS unit. Therefore, the variations of power generation from the wind turbine and PV units, in addition, the variation of

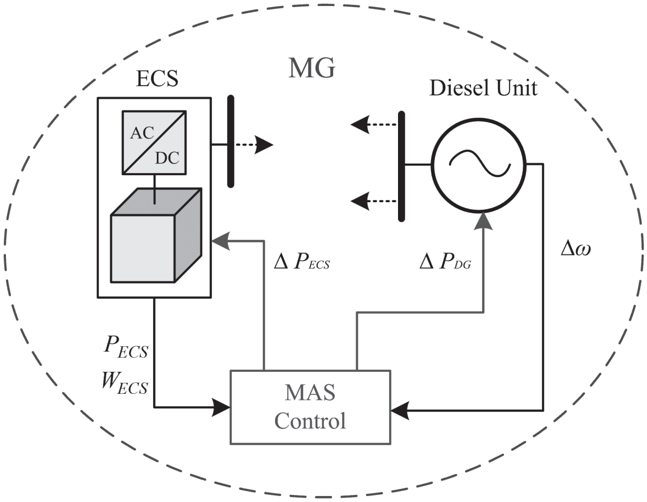

FIGURE 16-73 Multiagent-system-based coordinated ECS-diesel generator frequency control in MG.

demand power on the variable loads can be efficiently absorbed through the charging/discharging operation of the ECS unit. An additional regulation power (from the diesel units) is required to keep the stored energy level of the ECS in a proper range.

Figure 16-74 illustrates the dynamic configurations of the coordinated control loops for the diesel unit and ECS locating in the MAS control unit. In this study, the communication time delay is also

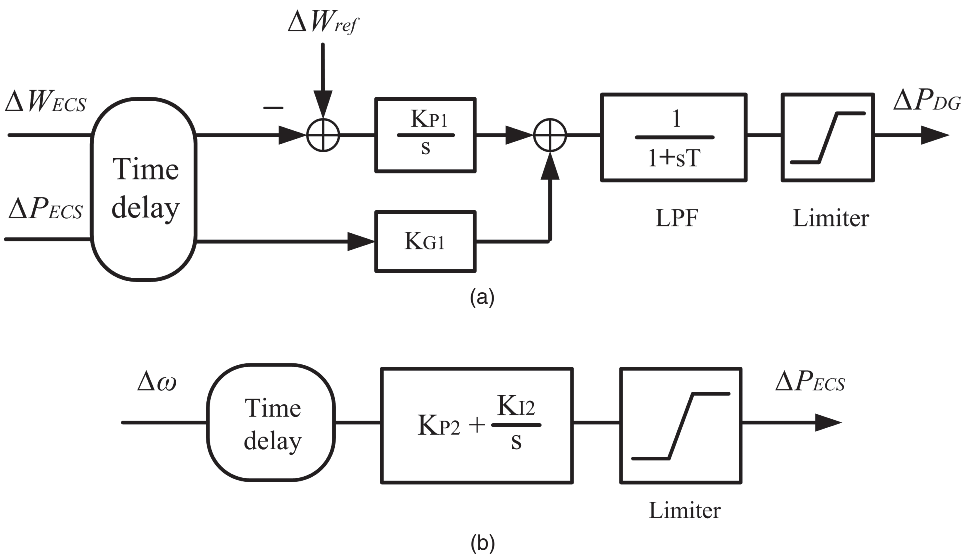

FIGURE 16-74 Coordinated control loops provided by supervisor agent for (*a*) ECS unit, and (*b*) diesel generator.

considered. ΔW_{ref} and ΔW_{ECS} are the target and measured available energies in the ECS. The ΔP_{ECS} and ΔP_{DG} represent regulation command signals for the ECS and diesel unit, respectively. (K_{P1}, K_{I1}) and (K_{P2}, K_{I2}) are proportional and integral constant gains for ECS and diesel unit control loops, respectively.

As mentioned, in the proposed supplementary control scheme, the ECS provides the main function of MG frequency control and the diesel unit provides a complementary function to support the charging/discharging operation on the ECS unit. Namely, a coordinated control between the ECS and the diesel units has been performed to balance the power demand and the total power generation in the MG.[13]

Frequency dependent battery charging can be used to enhance network frequency regulation capacity. The frequency regulation application could support the power balance related to some renewable energy resources which are of intermittent nature (e.g., wind and solar powers). As additional alternative, in coordination with other microsources, the frequency dependent charging of plug-in vehicles as distributed controllable loads can offer an effective way to improve the system frequency stability. Distributed controllable loads in cooperation with specified power reserve offer a resource that can rapidly react to the frequency disturbances.

The supplementary control also can be used to synchronize the MG before connecting to the main grid, to facilitate the transition from islanded to grid-connected mode. This issue can be usually performed in coordination with MGCC as the global supervisor. In contrary to the local controls, in supplementary controls, it may need to use low bandwidth communications.

16.9.5 Global Controls

Global control deals with some overall responsibilities for a MG, such as interchange power with the main grid and/or other MGs. These controls which are mainly done by a central controller, are acting in an economical-based energy management level between a MG and the neighbors similar to the existing supervisors for power exchanges and economic dispatch in a conventional multi-area power system. To meet the global control objective, a wide area monitoring and estimation is needed for many parameters and indices including fuel and devise storage conditions, commercial power cost and demand charge tariffs, generator reliability, real/reactive power components (power factor), feeder voltages, system frequency, equipment status, predicted weather, current/power spikes, system constraints, and load pattern.

Different control options are investigated for the MG central controller in different MG projects. In the CERTS MG in the United States,[18] this controller called MG energy manager is responsible for dispatching the output power and the terminal voltage of the DGs. Similarly, in the Hachinohe demonstration project in Japan,[19] economic dispatch and weekly operational planning are performed centrally. While, in the European architecture it is known as MG central controller (MGCC) and has several control functions.[10]

The MGCC interfaces the MG and the main grid, and also supervises the entire MG units for operations, such as disconnection, reconnection, power flow control, fault level control, market operating, and load shedding. The MGCC may also generate the power output set points for the DGs using gathered local information. Moreover, the MGCC controls power flow at the PCC to maintain closed to the scheduled value.

In a MG, identifying the optimal generation schedule to minimize production costs and balances the demand and supply which comes from both DGs and the distribution feeder, as well as online assessment of the MGs' security and reliability are the responsibilities of global controls. Global controls supervise the MG's market activities such as buying and selling active and reactive power to the grid and possible network congestions not only in the MG itself, but also by transferring energy to nearby feeders of the distribution network and other MGs. The global controls perform an energy management system (EMS) for MG to ensure a subset of basic functions such as load and weather forecasting, economic scheduling, security assessment, and demand side management.

The global controls for MG should be implemented through the cooperation of various controllers, located in all other levels, on the basis of communication and collection of information about distributed energy systems and control commands. This could be deployed by optimizing the power exchanged between the MG and the main grid, thus maximizing the local production depending on the market prices and security constraints. This is achieved by issuing control set points to distributed energy resources and controllable loads in order to optimize the local energy production and power exchanges with the main distribution grid.[20–23]

Following an islanding event, reconnection of the MG to the main grid can be also done by supervisory control via a controllable switch (SS), and the energy manager (MGCC) sends new power dispatch for participant microsources to provide their proportional share of load in MG. For the grid reconnection, the MG should be synchronized in phase with the main grid, and usually difference in frequency and voltage must be less than 2% and 5% (typically, 0.1 Hz and 3%), respectively. Table 16-24 shows the necessary limit values according to IEEE Standard 1547-2003[1] for frequency, voltage, and phase angle to achieve a synchronous interconnection between the MG and the main grid.

The local controllers such as MCs and LCs follow the orders of MGCC during grid-connected mode and have autonomy to perform their own controls during islanded mode. Furthermore, the MGCC may have different roles ranging from simple coordination of the local controllers to the main responsibility of optimizing the MG operation.[24]

TABLE 16-24 Limits for Synchronous Grid-Connected MG

DG's average rating (kVA)	Frequency deviation (Hz)	Voltage deviation (%)	Phase angle deviation (degree)
0–500	0.3	10	20
>500–1500	0.2	5	15
>1500–10000	0.1	3	10

16.9.6 Emergency Controls

In an MG, the connected DGs should meet some interconnection standards, and they also must have the capability of intentional disconnection in case of deviating from the specified standards for frequency, voltage, and phase angle (synchronization). For example, based on IEEE Standard 100-2000,[25] operating of DGs with nominal electrical output less than 10 kW in frequency range of 59.3 to 60.5 Hz is permitted. Otherwise, the DG should be disconnected from the network in no more than 10 cycles (about 0.16 s). For DGs with greater than 10 kW, the operating frequency range is reduced to 59.3 to 57 Hz.

The voltage constraints for DGs operation in connection mode are also considered by various standards. The requirement for disconnection usually is a function of the voltage deviation. Some cases cite a predetermined number of cycles for disconnection or tripping of DGs for a given voltage range. Typical voltage constraints for under/over voltage DG trips are given in Table 16-25.[26] For phase angle constraints, according to the IEEE Standard 2002,[27] typical utility requirements are that the source voltage deviation is no more than +10%, with the source waveform being no more than +10 degrees out of phase with the prevailing utility waveform.

In addition to the constraints for the individual microsources, the whole MG should also take advantage of operating in islanding mode, during power outage, block out, or emergency condition in the main grid, to increase the overall reliability of the power supply. In the emergency condition, an immediate change in the output power control of the MG is required, as it changes from a dispatched power mode to one controlling frequency and voltage of the islanded section of the network. After the initial reaction of the MCs and LCs, which should ensure

TABLE 16-25 Voltage and Maximum Number of Cycles for Under/overvoltage DG Trips

Voltage	Maximum number of cycles
$V < 50\%$	10
$50\% \leq V < 88\%$	120
$110\% \leq V < 120\%$	60
$V \geq 120\%$	6

MG survival following islanding, the MGCC performs the technical and economical optimization of the islanded system.

The islanding plan can be considered as most important emergency control scheme in the MG systems. When an MG system is islanded, the voltage/frequency might go beyond the power quality limits. Sometimes this transition is likely to cause large mismatches between generation and loads, causing a severe frequency and voltage control problem. Therefore, the islanding procedure requires a careful planning of the existing level of generation and load. In order to ensure system survival following islanding it is necessary to exploit controllable microsources, storage devices, local load as well as load shedding schemes and special protection plans in a cooperative way.[28]

Following islanding, the dependency of frequency and voltage on active and reactive powers allows each microsource to provide its proportional share of load without immediate new power dispatch from the higher level controller, for example, energy manager or MGCC in global control level. Therefore, in an islanded MG, the small generators are trying to maintain the MG voltage/frequency by controlling the reactive/active power. However, these control actions are not always adequate, and similar to the load shedding in the conventional power systems, following islanding, it may need to curtail some blocks of loads, firstly from nonsensitive parts.

Therefore, load shedding can be considered as an effective emergency control scheme in the MGs, too. Load shedding can be started in form of underfrequency or undervoltage load-shedding schemes (UFLS, UVLS). The UFLS and UVLS are working based on a significant drop in frequency and voltage, respectively. For example, in an islanded situation, when the loads in the MG are higher than total generation capacity, then frequency will go down. Therefore, some loads have to be shed to bring the frequency back within the permitted limit.

Similar to the global controls, the emergency controls can be also organized by the MG operator (MGCC). The performance of most existing controls in other levels, as well as the optimal control strategies for the MG are depending on the MG's operation state (islanded or grid connected); and switching between control strategies can be done through the operation mode detection. Hence, islanding detection (for unplanned cases) as a significant stage needs more attention; and effective techniques to satisfy the existing standards such as IEEE 1547,[1] IEEE 929-2000,[29] and UL 1741[30] should be used. The severity of the transients suffered by the MG after an unplanned islanding depends on many factors such as type and place of the disturbance/fault that starts the islanding, operation conditions before islanding, interval until islanding detection, commutation operations subsequent to a disturbance, type of microsources connected to the MG.[6]

Emergency control and protection schemes designed for conventional power systems with unidirectional power flow may become ineffective for modern power system with numerous distributed MGs and DGs. Undetected faults as well as unnecessary tripping or delayed relay operations may occur due to high DG penetration. It may also disturb the automatic re-closing operation. The operation sequence of protection devices during a fault is thus important.[31] Due to increasing of MGs/DGs, the existing methods used in a fault location could also become inappropriate.

The current operational practice of a distribution network requires the disconnection of MG systems when a fault occurs. This will keep the operational conditions simple and clear, safe and suitable for auto-reclosing. The purpose of MG connection point protection (e.g., frequency and voltage relays) is to eliminate the propagation of fault arc from the grid to the MG, and to prevent unintended island operation.

In an MG, the consequences of an immediate tripping of DG units may become adverse when a sudden change in a power index is seen by other DG units. Even during a fault at a MG network unnecessary disconnection of DG units and microsources may occur due to unwanted trips of feeder or DG unit protection relays, loss of synchronism, sustained overspeed and overcurrent of asynchronous generators or overcurrent and DC overvoltage of power electronic converters. The current operational practice clearly creates a contradiction between network safety and stability.

In the new distribution system with numerous MGs, the protection relays should be used among the gird, on the lowest level like in passive networks. Also new feeder protection schemes such as directional overcurrent, distance and differential protection, and new fault location applications are needed to be introduced. The protection in MG networks can be improved through advanced protection schemes and decentralized control of DG units.

Using advanced communication/networking technologies as another important issue has a significant role in MGs operation and control. Therefore, the design and implementation of new communication infrastructures and networking technologies for the MGs are key factors to realize robust/intelligent control strategies, specifically in emergency and global control loops. Power line communication (PLC), Internet protocol (IP)-based communication network, and wireless networking are common available communication/networking technologies. The employed communication/networking technologies should capable of supporting the control applications in a secure, efficient, and cost-effective way. On the other hand, the entire network infrastructure in an MG is also needed to be controllable and flexible to ensure that every application will perform well and be protected from attack or tampering.

16.9.7 References

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