Chapter 15
Hierarchical Control in Microgrid

Ersan Kabalci

Abstract It is required to utilize several control loops together to increase reliability and performance of microgrids. The current and voltage magnitudes, frequency and angle information, active and reactive power data provide the involved feedback for normal and island mode operations of microgrid. The hierarchical control structure of microgrid is responsible for microgrid synchronization, optimizing the management costs, control of power share with neighbor grids and utility grid in normal mode while it is responsible for load sharing, distributed generation, and voltage/frequency regulation in both normal and islanding operation modes. The load control of microgrid is performed by using more sophisticated electronic devices as well as regular circuit breakers. This regulation capacity could be improved since the ESS decreases the dependency to primary power sources. Although several improvements have been experienced in microgrid control strategies, the most intensive research areas are listed as decreasing the structural instability, improving the system performance to increase reliability, monitoring the harmonic contents, scaling the control infrastructure, enhancing the operation characteristics in error states, and implementing new control algorithms for normal and islanding operation. The microgrid system has hierarchical control infrastructure in different levels similar to conventional grids. The microgrid requires enhanced control techniques to manage any level of system. Safe operation of microgrid in both operation modes and connection and disconnection between microgrid and utility grid are depended to microgrid control techniques. The controllers should ensure to operate the system regarding to predefined circumstances and efficiency requirements. The hierarchical control methods and applications of microgrid infrastructure are presented in the proposed chapter.

Keywords Microgrid · Hierarchical control · Central controller · Microgrid hierarchy · Information and communication technologies · Distributed control

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N. Mahdavi Tabatabaei et al. (eds.), *Microgrid Architectures, Control and Protection Methods*, Power Systems,
https://doi.org/10.1007/978-3-030-23723-3_15

15.1 Introduction

The power network has gained more effective, flexible, and tended to distributed generation (DG) regarding to achieved technical and economic improvements. It is not possible to ignore contributions of communication technologies to these achievements. It is expected that the improved power electronics and equipments will play important role on development of power infrastructure in a few decades. This new grid trend enables the power network to be more distributed and interactive to integrate generation and consumption as two main components of grid infrastructure. In this regard, the increased use of distributed energy resources (DERs) have leveraged integration of energy storage systems (ESSs) to the same power plants. This new grid scenario that is also known as smart grid (SG) will enable to deliver generated electricity from plants to consumer by using digital communication and control technologies, and will allow consumers to control their consumption rates, to improve reliability and monitoring opportunities. The improved power network is much more interactive, smart, and distributed by comparing to conventional utility grid. The ESSs will facilitate to achieve energy balance among DERs and existing power network.

The microgrid infrastructure is one of the most important concepts of DG system and it cooperates with ESSs. Although the microgrid concept is improved to cope with integration of renewable energy sources (RESs) to power network, it is meaningful with participation of consumers to generation, energy storage, control, and management sections of power network. This improvement transforms consumers to prosumers by their active participation to generation cycle. There are extensive researches for DC and AC microgrids where hybrid microgrid applications have been developed [1–3].

The widespread use of RESs and penetration to utility grid over microgrids have caused several challenges and problems on reliability, resiliency, and control issues of both utility grid and microgrids. These challenges and control methods improved to cope with these challenges are presented in this chapter. There is an increasing interest on microgrid control and protection topics among reliability, security, and economical operating issues that are widely researched since a few decades. The achieved improvements in microgrid control have leveraged to improve grid potential and enabled high-scale microgrid integrations to utility grid. these improvements have not only enabled the individual or joint operation of microgrids with connection, interconnection, and disconnection cycles but also have provided to eliminate challenges met in the general operation of distribution networks.

This chapter deals with basic principles of microgrid control where local control, central control, emergency control, and general control principles are presented as initial control requirements. The control methods except general control are related to internal control requirements of microgrid while the general control method performs operating conditions of microgrid for interacting with neighbor microgrids and utility grid. On the other hand, hierarchical control functions and requirements are presented in the next section where internal control loops, primary, secondary, and tertiary control methods are introduced with application areas. The technical details and control requirements are presented in a comprehensive hierarchical structure regarding to central and distributed control operations in microgrid infrastructure.

15.2 Basic Principles of Control and Management in Microgrid

Control is one of the key components providing improvement of microgrid systems. The microgrid networks require similar control structures at different layers and in hierarchical orders. The reliability and sustainability of microgrid infrastructure depends to enhanced control methods that are effectively operated at each layer. The healthy operation of microgrid in normal and islanded operations modes, and successful integration or disconnection with utility grid is also depended to microgrid control techniques. The controllers should ensure smooth operation of entire system in the context of predefined operation conditions. It is known that microgrid does not only operate in autonomous islanded mode but also in normal mode. In the normal operation mode, voltage and frequency of microgrid should comply with amplitudes of utility grid. In this sense, microgrid should have appropriate control loops for ensuring active power/frequency (P/f) regulation, reactive power/voltage (Q/V) regulation and to react instant grid disturbances that are caused by ever-shifting load conditions. Moreover, detection algorithms of island mode are required to prevent sequential problems occurring during island mode and normal mode shifts.

A general schematic presentation of control methods used in microgrid operations is illustrated in Fig. 15.1. The whole microgrid model is controlled by a microsource control system (MCS) in this presentation. The load controllers (LCs) are used to manage controllable loads located in load models as its name implies. A central controller (CC) is located between microgrid and distribution management system (DMS) or distribution system operator (DSO) for each microgrid infrastructure. These controllers are responsible to perform medium voltage (MV) and low voltage (LV) controls in systems where more than single microgrid exists. Several control loops and layers as in conventional utility grids also comprise the microgrids. This hierarchical control scheme meets fundamental infrastructure and dynamic interface requirements in addition to providing integrity through central and distributed control systems [4].

The local control includes primary control systems such as voltage and current control loops that are used in DG and RES integration. The secondary control is essential to regulate frequency and average voltage fluctuations caused load or source variations. The secondary control is also responsible for local auxiliary services. Central and emergency control layer operates featured protection and emergency control protocols against unexpected events in the context of microgrid reliability. The emergency control techniques perform fault estimations by realizing protective and regulative measurements. The general control ensures economical operating conditions of microgrids by arranging the organization between microgrids and dis-

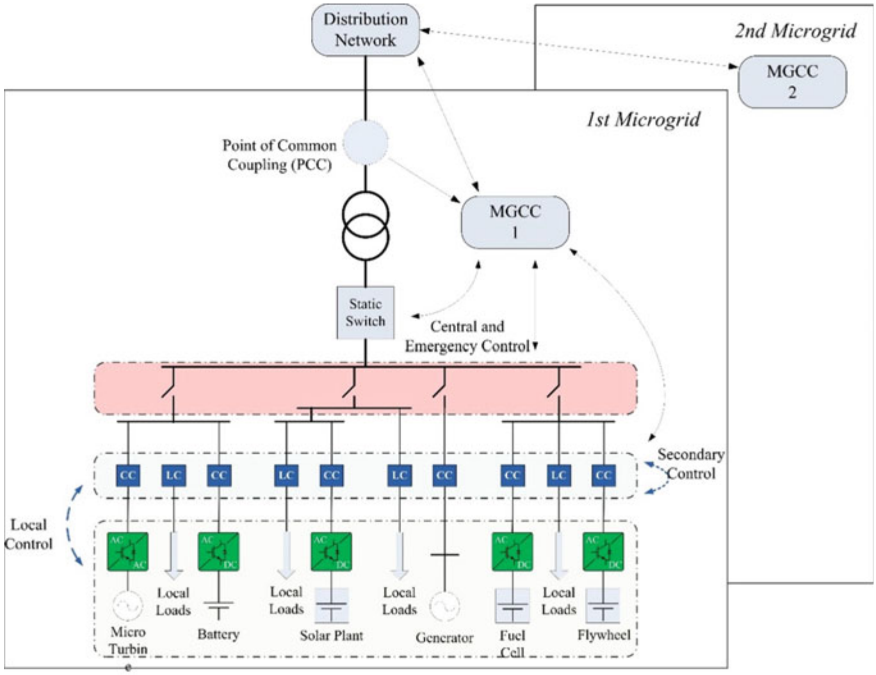

Fig. 15.1 A general view of microgrid control structure

tribution networks. The general control infrastructure seen in Fig. 15.1 operates as a distribution network interface for microgrid central controller (MGCC) and manages the power flow control. This control interface provides power distribution at predicted values by controlling the microgrid infrastructure. In spite of local control, the secondary, general and emergency control infrastructures require communication channel [5–7].

The local controllers used in microgrid are defined as distributed controllers while secondary and emergency controllers operate as CCs. The processes of general control level take from a few minutes to an hour and general controller transmits control signal to controllers at central level and to interconnected distribution systems. On the other hand, CC is capable to coordinate secondary controllers and local controllers in the microgrid in a few minutes. The secondary control mechanism can react to system disturbances or control commands in a few seconds to a minute. Eventually, local controller systems are designed to operate in an independent way and according to predefined event schedules. The detailed introduction of LCs, secondary controllers, general controllers, central and emergency controllers are presented in the following sections.

15.2.1 Local Control

The local control is known as primary or internal control and comprises the primary level of hierarchical control. This control method that has the most rapid response time can vary regarding to microgrid type and is used in asynchronous and synchronous generators, power electronic inverters and converters. The power electronic devices provide flexible operating conditions comparing to those in synchronous and asynchronous generators. The local controllers are mostly operated with internal control loops that do not require communication, with low cost and simple device structures. The local controllers are the most basic category of microgrid control that targets to manage DG under normal operating conditions.

A DG local controller of power electronic inverter that is operated regarding to reference voltage inherited from conventional droop controller is shown in Fig. 15.2. The droop controllers calculate virtual inertia of each parallel-connected inverter by determining average *P* and *Q* power depending to frequency and voltage values of inverters. These control loops that are also known as *P–f* and *Q–V* enable inverters to be connected in parallel as uninterruptible power supplies (UPSs) and load sharing operations. Although these methods provide reliability and flexibility, it is known that there are some drawbacks exist in conventional droop control. For instance, droop control method does not properly operate in non-linear load sharing requirements of parallel-connected systems since it needs to consider harmonic currents and active-reactive power balance. Therefore, a novel method called harmonic current sharing is improved to eliminate circulating distortions occurred in non-linear load sharing conditions. The developed control methods cause to voltage distortions while sharing harmonic currents, and thus it is required to acquire an average value among two situations [1, 5, 7–9].

The voltage and frequency control loops of a local controller is illustrated in Fig. 15.2 where the controller uses current measurement that is inherited from transfer function of virtual impedance as the feedforward signal. The proportional-integral

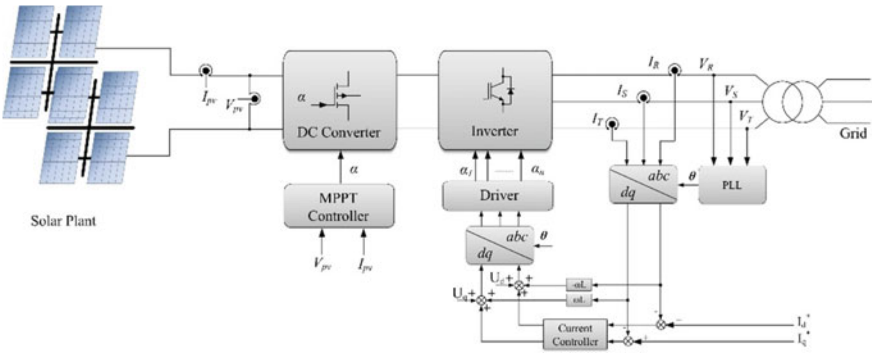

Fig. 15.2 A general view of local controller used in DG

(PI) observer is widely used in droop controllers that are located at local control level. The PI observers are used either individually in open control loops or with feedforward compensator in a closed loop to improve system performance.

These kinds of controllers are essential for managing operation conditions of DERs and power electronic interface as seen in the above example. In addition to primary V and f controls, it is required to control P and Q power in DG processes. The droop based active and reactive power controls are the most widely used methods in this context. Moreover, the control among sources is also handled in this context similarly to DG output control. To this end, inner control loop is used for current and outer control loop is used for voltage control in output control of DG system. The power sharing control provides active and reactive power control regarding to frequency and voltage fluctuations that are inherited from local measurements without any communication requirement.

The local controller designs are based on detailed dynamic models of distribution network parameters and resistive, inductive, and capacitive load profiles of DERs. This model requires to response immediately to internal dynamics and transient-state fluctuations of controller system. There are three basic reference frames as natural (abc), rotating (αβ) and synchronous (dq) exist for modelling, stability analyses, and synthesis of local control in inverter-based DG system. The natural reference frame is controlled with fundamental observers such as PI, and DG provides essential results for time axis response analyses of microgrid in time-domain. The rotating reference frame is mostly related with sinusoidal variables and synchronous reference frame operates with DC components and controllers [4].

15.2.2 Secondary Control

The secondary control is comprised by second level control loops that are used to enhance system performance by eliminating reliability problems and to increase power quality of microgrid network. The secondary control closely works with LC and CC groups. In normal operation mode, the inverters through the microgrid inherit reference electrical signals from voltage and frequency data of utility grid. On the other hand, inverters lose the reference signals provided by utility grid in the island mode operation. It is required to coordinate the cooperation of synchronized operation by using single or multiple operation methods. The secondary controllers include various control mechanisms to improve parallel operation performances of inverters or DGs. There have been several studies reported in literature on control of DGs, master and slave operation of inverters, current and power sharing, and generalized frequency and droop control [10–14].

The secondary control of microgrid operates similar to that of conventional power systems to prevent frequency fluctuations occurred in load shifts, to ensure stable and reliable voltage, and to operate local controllers in island mode operations; i.e., the voltage and frequency reference signals (E^* and ω^*) depicted in Fig. 15.3 are provided by secondary control loops. The secondary control loops represent rela-

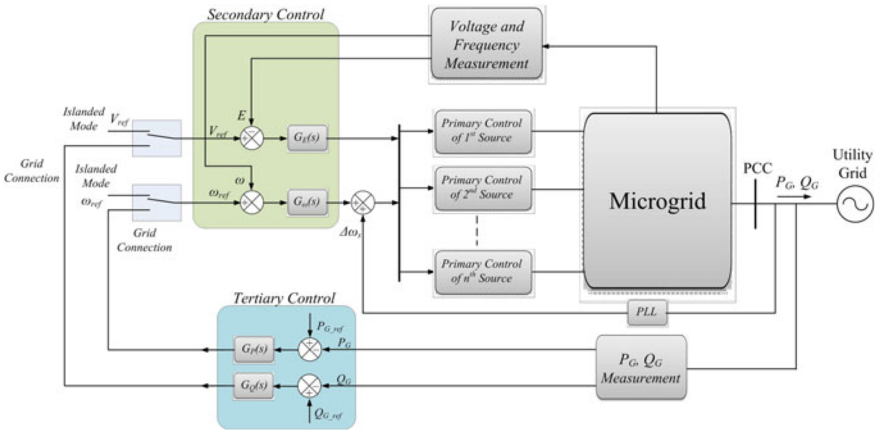

Fig. 15.3 The secondary and tertiary controllers in distributed generation

tively slower response times comparing to primary controllers, and thus they require low bandwidth communication. The improvement of power quality of DG sources connected at a common power line is also accomplished by secondary control. The integration of a secondary control system to central controller has been illustrated in Fig. 15.3 where the frequency and voltage of microgrid is compared to parameters of DG system that are used as reference values, ω_{ref} and V_{ref}. Afterwards, the generated error signals are evaluated by independent controllers to compensate frequency and voltage fluctuations [10, 15].

15.2.3 Central and Emergency Control

The central and emergency control concepts imply the central energy management system (CEMS) that is responsible for secure, reliable, and economic operation of microgrid in islanded and normal operation modes. The fundamental duties of this control level are active and reactive power control, voltage and frequency control, regulation, system restoration, and control of existing DG system for load shedding and featured protection procedures. The central and emergency control that has significant roles in islanded operation of microgrid is the control mechanism located on top of hierarchical control. Moreover, central control is used for synchronization of microgrid during shifting from island mode to normal mode. This operation is accomplished by coordinating the central controller and management system. The block diagram illustrating the coordinations of local, secondary, and central controller in voltage and frequency regulation is shown in Fig. 15.4 where the common role is also denoted.

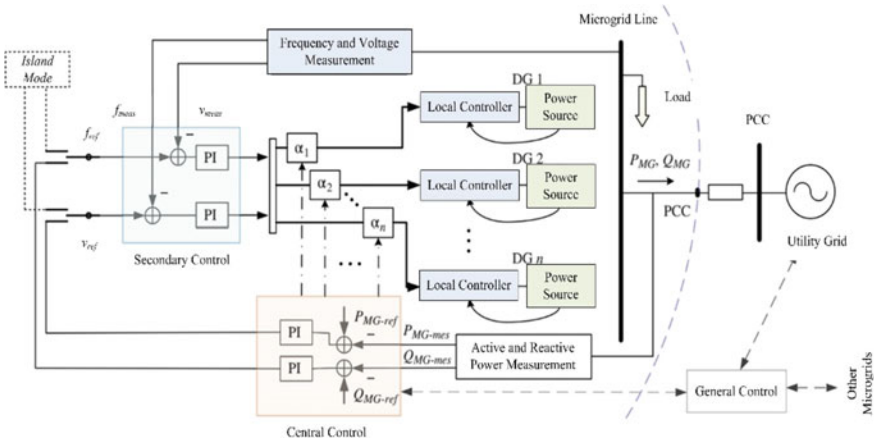

Fig. 15.4 The secondary, local, central and general control structure

While the utility grid is supported by auxiliary services of microgrid, the general control is also integrated to system under these operation conditions. The power flow between utility grid and microgrid is adjusted by using voltage and frequency of DG sources in normal operation mode as seen in Fig. 15.4. The active and reactive output power of microgrid are measured at the first step and then these amplitudes are compared to reference values (P_{ref}, Q_{ref}) to generate voltage and frequency references (f_{ref}, V_{ref}).

The inherited references are then used as the input parameters of secondary control. The α values denote contribution rate to voltage and frequency regulation for each DG sources located in the microgrid. A secondary control signal is generated and is distributed to each DG sources along the microgrid for detecting the load distortion and thus, each DG source is expected to compensate its generation-load imbalance by providing appropriate contribution.

The coordinating microgrids are much more essential against intermittency, outages and emergencies comparing to single microgrid structures. Besides, the collaborating microgrid connections improve the reliability of entire grid system by benefiting advantages of coordinated operation. The output power control of microgrid is adjusted to regulate power mode and frequency-voltage controls in emergency conditions. The island mode planning is assumed as the most significant emergency control systems for microgrid systems. Once a microgrid shifts to island mode, the voltage and frequency magnitudes can excess power quality limits. Therefore; DG sources, ESSs, load shedding at local loads, and particular protection schemes are required for ensuring to sustain islanded mode operation of microgrid. The load shedding procedure is an emergency control method that is operated when a significant loss is experienced in voltage or frequency magnitudes. Central controller of microgrid operates the emergency control. The improved communication and network technologies play crucial role in microgrid operation and control processes.

Therefore, information and communication technology (ICT) is an indispensable component of central and emergency control mechanisms in microgrid [2, 4, 12, 15].

15.2.4 General Control

The general or global control is also known as tertiary control that provides cooperation of microgrids with utility grid by using communication infrastructure. The general control ensures power control between utility and microgrids. On the other hand, microgrid can be dispatched in terms of distribution grid and can be controlled as a continuous inductance load if it is analyzed in the view of control perspective. Moreover, the general controller acts as a central controller to manage optimum power flow at point of common coupling (PCC) in addition to its duties on sustaining reliability and security of distribution feeders, generation planning, and active and reactive power flow controls.

The general controller is converted to central controller that manages demand side management (DSM), security controls, economic planning, and load estimation functions. Eventually, the general control level is responsible for facilitating the operation conditions of microgrid and improving the operation of distribution buses by controlling active and reactive power rates of DG sources. These improvements are usually related to economic conditions and target to ensure demand and generation balance [4, 6]. The detailed presentation of general control is conducted in tertiary control section of hierarchical control.

15.3 Hierarchical Control

Microgrid control standards are expected to find widespread use in near future. In this regard, ISA95 is the most widely used standard to improve an automatic interface between operation and control systems. The fundamental task of ISA95 is to provide a convenient terminology defining how the data will be used between service provider and producer communication. The hierarchical control that is defined in the context of this standard includes multilevel control structure:

5th Level: This level includes the highest management principles throughout a commercial enterprise. The operation, improvement responsibilities, transmission lines, and plants are controlled at this level.
4th Level: The plant level is directly related with economic and financial operations that are required for management strategies.
3rd Level: This level accommodates situations of generation systems and their behaviours for management requirements.

2nd Level: This is the level where management and control strategies are defined on a particular area or generation line behaviours.
1st Level: This level includes predefined management procedures for automation and generation systems.
0th Level: The device level is comprised by physical connections and equipments to detect changes occurred in peripheral and generation systems.

Each level includes a command section and performs managed control on low ordered systems. It should be noted that a control and reference signal transferred from higher level to lower one has little effect on system reliability and performance. Therefore, it is required to decrease the bandwidth as the control level increases. The integration of ISA95 standard to any microgrid infrastructure requires following control levels from 0th level to 3rd level [1]:

0th Level Control (*Internal Control Loops*): The regulation of each module is performed at this level. It is provided to obtain reliable output voltage and current by using current, voltage, feed-forward, feedback, linear and nonlinear control loops.
1st Level Control (*Primary Control*): The droop control method is widely used in this level and the physical operations are virtually performed to increase system stability. This level is also used for modeling the physical output impedance of system by using virtual impedance control layer.
2nd Level Control (*Secondary Control*): This control layer ensures to obtain output voltage and currents of microgrid at the desired values. Moreover, it operates synchronization control loop to enable appropriate connection and disconnection with utility grid.
3rd Level Control (*Tertiary Control*): This control level controls power generation and power flow between microgrid and utility grid.

Nowadays, these control methods have been extensively used in penetration of solar plants and wind turbine systems to microgrid and utility grid. In addition to this, microgrid infrastructures that can be operated in islanded and grid-connected modes increased the hierarchical control and energy management requirements. There are numerous studies have been published on hierarchical control, coordinated control, frequency control, and tertiary level control in the recent literature [5, 9, 16–18]. The main problem to be solved seems as frequency control according to majority of literature surveys. However, voltage reliability and synchronization are also researched in order to provide reliability and flexibility to both operation modes of microgrids. The primary control is based on internal control loops such as voltage, frequency, and droop control while secondary control is related with synchronization and coordination regarding to load shedding, grid monitoring, active and reactive power control. The tertiary control provides microgrid management controls such as ICT based measurements, remote monitoring and remote-control procedures.

15.3.1 Internal Control Loops

It is mandatory to comprise an interface by using intelligent electronic systems between DG sources and microgrid. These interfaces are provided either by current source inverters (CSIs) that include phase locked loop (PLL) for grid synchronization and internal current loop or by voltage source inverters (VSIs) including an internal current loop and an outer voltage control loop. CSIs are used to provide stable current or VSIs are used to provide stable voltage to grid in island mode or autonomous operations. VSIs present an interesting operation since they do not need any external reference to sustain grid synchronization in microgrid applications. Moreover, VSIs provide significant contribution to DG power systems by improving power quality and sustaining the operation under fault conditions. These inverters can be converted to CSIs on demand in normal operation modes. Although the CSIs may operate as VSIs on demand, they are mostly connected to solar or small wind turbines that are operated by maximum power point tracking (MPPT) algorithms. Thus, a string comprised by CSI and VSIs or just VSIs are connected in parallel to comprise power electronics interface of microgrid [4, 16].

15.3.2 Primary Control

When two or more VSI are connected in parallel, the active and reactive power circulation occurs as seen in Fig. 15.5. This control level adjusts the reference voltage and frequency values that are provided to internal current and voltage control loops. The fundamental idea of this control level is to mimic behaviors of a synchronous generator that decreases frequency while active power is increasing. This process is the use of widely known P–Q droop control in VSI control where the analytical presentation is as follows:

$$\omega = \omega^* - T_P(s)(P - P^*) \tag{15.1}$$

$$V = V^* - T_Q(s)(Q - Q^*) \tag{15.2}$$

where, ω and V denote frequency and voltage of output reference voltage while ω^* and V^* are reference of them, P and Q are active and reactive power, P^* and Q^* are references of active and reactive power, and $T_P(s)$ and $T_Q(s)$ are related transfer functions.

The general representation of proportional droop control that is illustrated in Fig. 15.6 is defined as $T_P(s) = m$ and $T_Q(s) = n$ transfer functions where DC components m and n are calculated as presented below:

$$m = \Delta\omega / P_{\max} \tag{15.3}$$

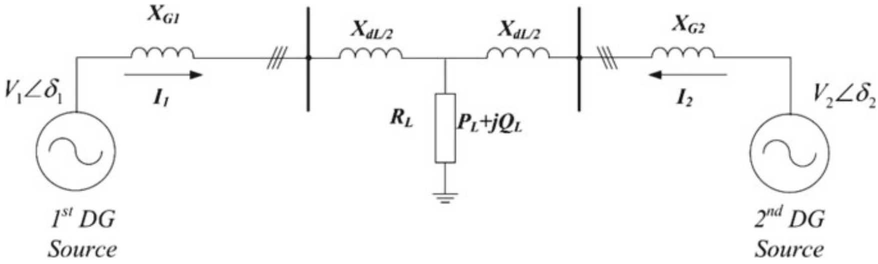

Fig. 15.5 Electrical equivalent circuit of parallel connected two inverters

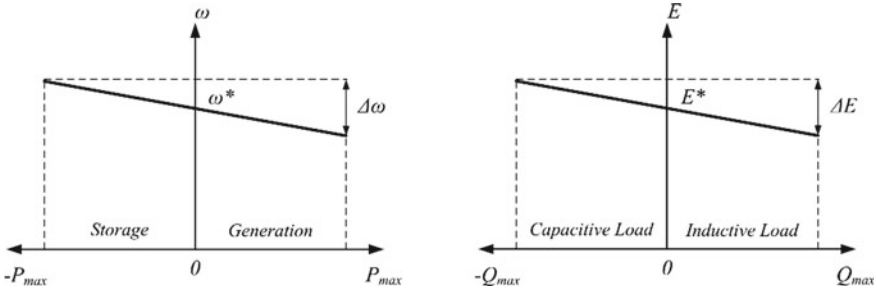

Fig. 15.6 *P*–*Q* droop control functions

$$n = \Delta V/2Q\text{max} \tag{15.4}$$

Since the transferred power will not be equal to total load in islanded mode operation of microgrid, it is not allowed to design a controller that is based on just a pure integrator. Although it may be essential for detecting the accurate rates of P and Q power that are transferred to grid during normal operation mode, the most accurate rates are detected at tertiary level control. The compensators of $T_P(s)$ and $T_Q(s)$ can be designed by using various control synthesis techniques. Moreover, the DC gain of these compensators m and n control the $\Delta P/\Delta\omega$ and $\Delta Q/\Delta V$ fluctuations that ensure system synchronization and voltage limits [1, 10].

The output impedance of synchronous generators is mostly assumed inductive as transmission lines in classical droop control of large power systems. In addition to this, the output impedance of those systems using power electronics may vary depending to internal control loops at fundamental level. On the other hand, it draws almost resistive characteristics in low voltage applications. Therefore, the Eqs. (15.1) and (15.2) can be rearranged as follows regarding to Park transformation using impedance angle θ:

$$\omega = \omega^* - T_P(s)[(P - P^*)\sin\theta - (Q - Q^*)\cos\theta] \tag{15.5}$$

$$V = V^* - T_Q(s)[(P - P^*)\cos\theta + (Q - Q^*)\sin\theta] \tag{15.6}$$

The primary control should meet fundamental requirements such as stabilizing voltage and frequency, plug-and-play operation capability for DG sources, active and reactive power sharing without communication, and decreasing the circulating currents. The reference current and voltage control loops of DG sources are generated by primary control using fundamental level or zeroth level controls that are operating in P–Q or voltage control modes. The voltage and current control loops of this system is shown in Fig. 15.7 where the controller uses current signal as a feedback transfer function in virtual impedance operation. An appropriate control is performed by using one of proportional-integral-derivative (PID), adaptive or proportional resonance (PR) controllers as voltage controllers. The power quality of small scale and islanded microgrids are particularly important since the microgrid has low inertia and characteristics of single-phase loads are not linear [10, 11].

Therefore, the power quality can be increased by parallel connecting a number of strings as shown Fig. 15.8. The $H_{LPF}(s)$ depicts the transfer function of a low pass filter in the figure where each converter has an independent current control loop and a central voltage controller distributes fundamental component of active and reactive power between different sources.

Primary controller determines the reference point of voltage control loop and independent current controllers enhance the power quality of entire system by controlling the harmonic components in the current that is provided to utility grid. The DG source operation mode is accomplished by using active load sharing or droop characteristic control methods. The active load sharing is a kind of control procedure that is used in parallel-connected inverters and is based on communication capability. The current or active-reactive power references are determined according to central, master-slave, average load sharing or circular chain control methods. In the central control method, all the load currents are controlled regarding to reference current that is determined for a single inverter. On the other hand, a master converter operates as VSI and other converters tending as slaves operates as CSIs that are tracking the current reference value defined by master VSI in master-slave control method. In average load sharing control, the required current reference is determined considering weighted average value of all independent converters. The circular chain control method considers converters as chains that are connected to each other, and the current reference is determined regarding to previous converter. The active load sharing

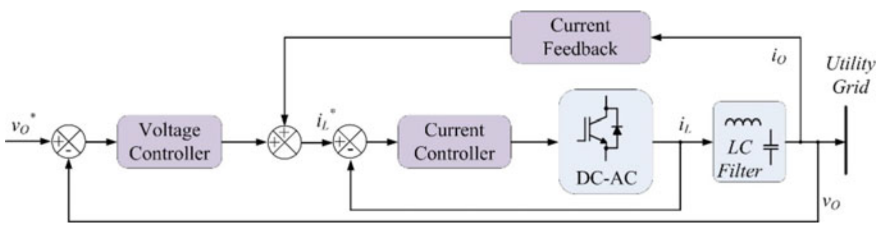

Fig. 15.7 Voltage and current control loops in voltage control mode

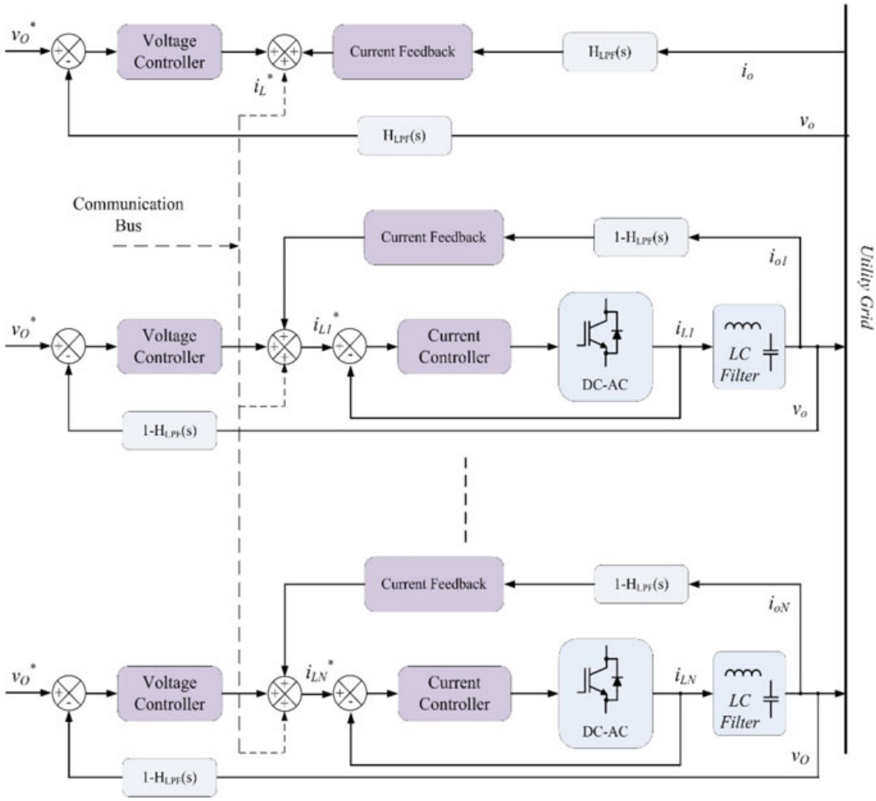

Fig. 15.8 Zero level control of parallel-connected DG sources

method requires communication buses and high bandwidth control loops. However, it provides highly accurate current sharing and power quality among others [19].

The droop control is known as independent, autonomous and wireless control method since it eliminates communication requirement through converters. The operation principle of classical droop control can be explained considering electrical equivalent circuit of a VSI that is connected to AC line. If the switching fluctuations and high frequency harmonics are neglected, the VSI can be modelled as an AC source with $E\angle\theta$ voltage. Also, common AC line voltage, output impedances of converter and line impedances can be accepted as a single-circuit line model with $V_{com}\angle 0$ impedance [19]. The power transferred to AC line is then calculated as:

$$S = V_{com}I^* = \frac{V_{com}E\angle\theta - \delta}{Z} - \frac{V_{com}^2\angle\theta}{Z} \tag{15.7}$$

The active and reactive power can be dispatched as follows by using Eq. (15.7) and obtained as:

$$\left.\begin{aligned} P &= \frac{V_{com}E}{Z}\cos(\theta-\delta) - \frac{V_{com}^2}{Z}\cos(\theta) \\ Q &= \frac{V_{com}E}{Z}\sin(\theta-\delta) - \frac{V_{com}^2}{Z}\sin(\theta) \end{aligned}\right\} \tag{15.8}$$

and they are rearranged as seen in Eq. (15.9) by assuming the line impedance is pure inductive $Z\angle\theta$:

$$\left.\begin{aligned} P &= \frac{V_{com}E}{Z}\sin\delta \\ Q &= \frac{V_{com}E\cos\delta - V_{com}^2}{Z} \end{aligned}\right\} \tag{15.9}$$

15.3.3 Secondary Control

The secondary control level is improved to compensate voltage and frequency fluctuations in microgrids. The secondary control manages regulation process to eliminate the fluctuations in case of any load or generation changes. The voltage and frequency levels of the microgrid V_{MG} and ω_{MG} are immediately detected anc compared to reference values, V_{MG}^* and ω_{MG}^*. The error signals (δV and $\delta\omega$) that are processed in compensator block are transmitted to each section of the system and output frequency and voltage are get regulated. It is known that the allowed maximum frequency fluctuations are ±0.1 Hz in North Europe while it is ±0.2 Hz in central Europe. This situation is denoted with

$$\delta P = -\beta G - \frac{1}{T_k}\int G dt \tag{15.10}$$

where output reference of secondary controller is depicted by δP, proportional controller parameter is given by β gain parameter, and T_k is time constant of secondary controller while G denotes field control error. The block diagram of primary and secondary control loops is shown in Fig. 15.9. The primary control is based on local measurements of output voltage and currents, virtual impedance control loops, and droop control of P–Q values. On the other hand, the secondary controller operates as a central controller that is improved to regulate frequency and voltage fluctuations presented in Eqs. (15.11) and (15.12) [1]:

$$\delta\omega = k_{p\omega}(\omega_M^* - \omega_M) + k_{i\omega}\int(\omega_M^* - \omega_M)dt + \Delta\omega_s \tag{15.11}$$

$$\delta V = k_{pV}(V_M^* - V_M) + k_{iV}\int(V_M^* - V_M)dt \tag{15.12}$$

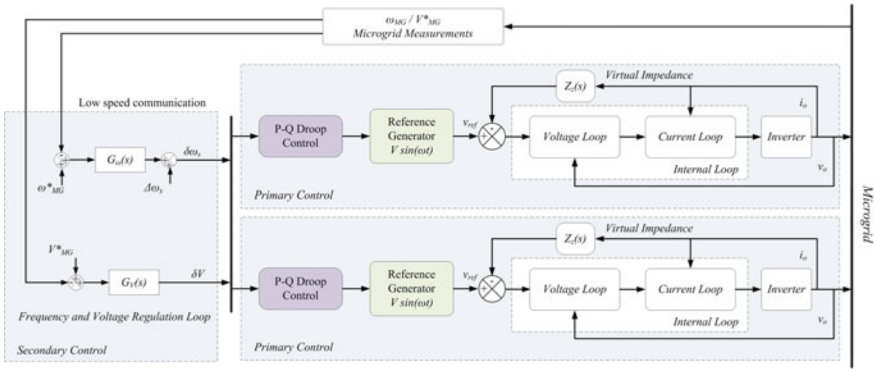

Fig. 15.9 Primary and secondary control in AC microgrid

The microgrid connection to utility grid is depended to voltage and frequency measurements of main grid and usage as references in secondary control. The phase differences are regulated and synchronization is performed by PLL algorithm acting as synchronization control loop. The output signal $\Delta\omega_S$ is transmitted by secondary controller through the entire system for synchronization that is completed within a few cycles and microgrid is connected to utility grid. The dynamic response of secondary control is relatively lower than primary control systems [1, 10, 15, 20].

15.3.4 Tertiary Control

The tertiary control is the highest level in hierarchical control structure, and has the lowest operation speed among others. This control level is related with economic and optimum operation of microgrid and manages power transmission through utility grid. The power transmission is controlled by adjusting voltage and frequency of DG sources in normal operation mode as presented earlier in Fig. 15.3. The control system initially detects output powers P_G, Q_G of microgrid and then compares these measurements with reference values P_{REF}, Q_{REF}. After the comparison process, the voltage and frequency references V_{REF} and ω_{REF} are obtained as presented below:

$$\omega_{REF} = k_{PP}(P_G^{REF} - P_G) + k_{iP}\int (P_G^{REF} - P_G)dt \tag{15.13}$$

$$V_{REF} = k_{PQ}(Q_G^{REF} - Q_G) + k_{iQ}\int (Q_G^{REF} - Q_G)dt \tag{15.14}$$

The parameters K_{PP}, K_{iP}, K_{PQ}, and K_{iQ} denotes control coefficients, and V_{REF} and ω_{REF} are used as reference values for secondary control procedure. The tertiary control ensures that all the DG sources are operated at equal marginal costs

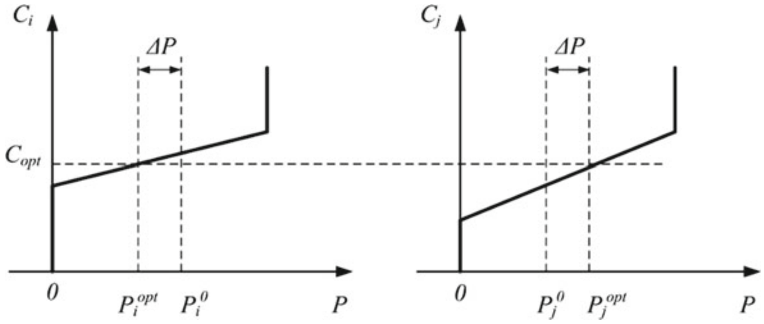

Fig. 15.10 Marginal cost detection of two separate DG source along microgrid

to provide optimum economic operation of entire microgrid. This control process is accomplished by using an algorithm that defines an optimum cost coefficient C_{opt}. The predefined coefficient selects arbitrary initial starting power values with i and j for DG sources as P_{oi} and P_{oj}. Thus, the algorithm operates iterations until the starting values are reached to optimum values and calculations are repeated to detect required output power of DG sources. Once the required power value has been calculated, the control commands are generated to force DG sources to generate desired output power. The operation principle of search algorithm is illustrated in Fig. 15.10 for i and j DG sources [10].

The searching procedure is performed for each pair of DG sources along microgrid and all the sources are forced to operate in optimum conditions. Several algorithms based on game theory and other metaheuristic algorithms have been improved to facilitate communication requirement. Thus, it is researched to easily obtain the local measurement results [1, 10, 13].

15.4 Central and Distributed Control in Microgrid

It became mandatory to use intelligent power electronics between microgrid and generation sources. These infrastructures have output stages based on CSI or VSI interfaces as discussed earlier. A microgrid control infrastructure is composed of a number of central and distributed controllers. The central controllers are connected to MGCC to improve and enhance operation features of microgrid. The MGCC determines demand power, enhancement conditions and load capacities considering the auxiliary services of distribution system. The defined enhancement and operating scenarios are performed by transmitting control signals to controllable field loads and microgrid controllers. The non-critical and flexible loads can be shaded from grid if it is required. Moreover, active and reactive power measurements should be performed instantly. In the complete distributed control approach, microgrid controllers cooperate with other controllers to transfer the available maximum power to grid by considering market conditions. This approach is improved to tackle MGCC problems met in the systems where many DG sources exist and decisions are made locally.

Regardless the controlled microgrid characteristics and main tasks, the decision on use of central or distributed control is made considering current equipment and staff situations. The block diagrams of central and distributed control systems are shown in Figs. 15.11 and 15.12 respectively. Both systems include local functions such as local generation, demand estimation and security monitoring. The significant criteria of each system are based on calculation period, scalability, and accuracy that all are related with complexity of algorithm [6].

Several micro sources and controllable loads that may cause complexity and latencies due to numbers of DG source comprise a microgrid. The sources and loads are mostly distributed along the microgrid and they operate with low bandwidth communication system in low voltage level. The low bandwidth may cause message transmission problems when high ordered control hierarchy is used. Therefore, the complexity of control system should be considered to prevent missing of control commands and communication messages. The decision on microgrid control that are defined by different system operators can increase the node number in addition to technical complexities. Another important issue to be considered is data communication level that can be defined by different system operators to decide which parameters will be used and whether there will be any prevention policy.

The reliability is also an important issue for microgrid control system. The outcomes of any algorithm should be accurate and reliable to control the microgrid. The selection of central or distributed control approach is performed considering the requirements of microgrid and particular needs where the conditions are listed in Table 15.1 [6]. In case users have common targets and common operation conditions, the central controller will be the most appropriate for this type of microgrid. When an industrial microgrid considered, a generation provider may control all the

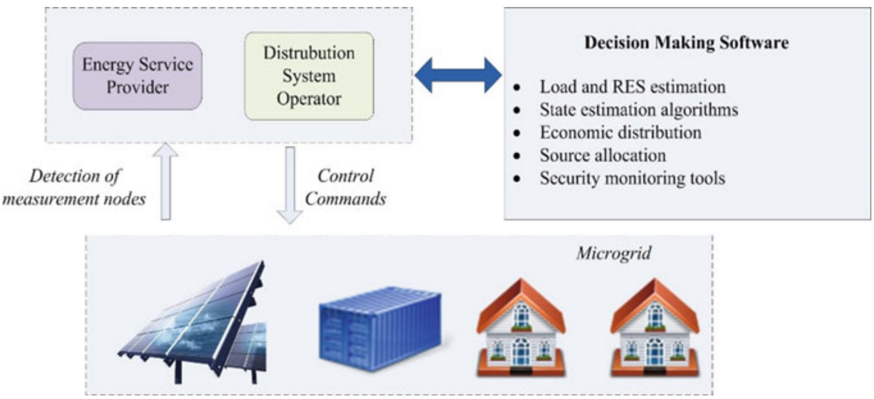

Fig. 15.11 Central controller system

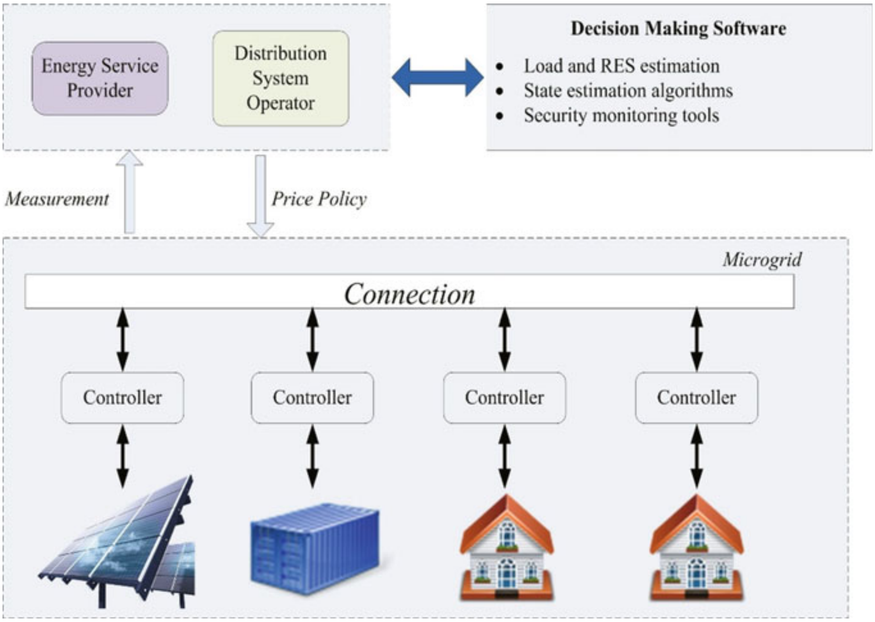

Fig. 15.12 Distributed control system

Table 15.1 Features and differences of central and distributed control systems

Feature	Central control	Distributed control
DG source ownership type	Single ownership	Joint ownership
Targets	Single and main task (i.e. cost decrement)	Each owner may have different target
Staff and source requirement	Exists	Does not exist
Market participation	Complex algorithms	Simple algorithms
New equipment installation	Requires qualified staff	Plug-and-play
Communication requirement	High	Medium
Critical system connection	Possible	Not possible

DG sources and loads, may monitor the situations of generation and consumption or may perform arrangements for economic operation.

It is possible to install faster communication infrastructure and sensor nodes by limiting the measurement and transmission node numbers as discussed earlier. Moreover, specific researches are done to decrease facilitation and cost decrement problems. A microgrid operating under market conditions and requiring competitive precautions need to be controlled by mostly independent and intelligent systems. The local DG source owners may also have different expectations such as cooling, protecting the critical loads and backups in addition to power transfer to utility grid.

A DG platform may include dozens of such neighboring small microgrids with their subgrid infrastructures. The classification of data transmission requirements and management decreases the costs and allows owners to control their microgrid in efficient ways. On the other hand, the distributed calculation technology enables plug-and-play operation of DG sources and accelerates integration to microgrid that provides flexible and secure monitoring infrastructures.

15.5 Conclusion

This chapter presents fundamental and improved control structures of microgrids. The basic control principles are presented in classification of local control, secondary control, central and emergency control, and general control methods that are related with hierarchical control concept. The local control is known as primary level control that is responsible for operating internal control loops to improve stability of microgrid. It is based on device level where physical and power electronics controls are performed. The hierarchical control is performed by using primary, secondary and tertiary level controllers along the microgrid structure to ensure maximum power transmission to utility grid in normal operation mode. Therefore, power quality of microgrid should be improved by using secondary control in addition to voltage and current improvement in primary control. The secure, reliable and sustainable control of microgrid is depended to healthy operation of hierarchical control. General or global controllers that ensure to obtain optimum power level at PCC manage the tertiary control structure. Although the basic control principles seem similar to hierarchical control infrastructure, they differ in organization scheme where hierarchical control system includes three control levels in a single microgrid to cooperate with neighbor microgrids and utility grid.

The tertiary control is required to ensure economic operation of microgrid in both operation modes. Moreover, central or distributed control strategies are considered to determine the appropriate control scheme for any microgrid. The features and selection criteria of central and distributed control schemes are tabularized in the last section. The presented researches have outlined that intelligent control systems are much more efficient on power sharing and decreasing the voltage and frequency fluctuations. The improved control methods are widely researched to enhance power quality and operation conditions of microgrids interacting neighbor microgrids and utility grid.

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