# Microgrid Control: A Solution for Penetration of Renewable Power

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# Microgrid Control: A Solution for Penetration of Renewable Power

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***Abstract*—The *microgrid* concept provides a quite appealing solution for overcoming the challenges of integrating renewable energy sources and distributed generators into power grids. Advances in the microgrids control have improved the microgrids potential to be integrated into the conventional electrical systems in a higher capacity. This improvement not only covers their internal control performance and connection/disconnection procedures in order to limit the negative dynamic impacts in the network and other connected microgrids, but also includes the grid support functionalities to enhance the global operation of distribution networks. In this paper, a general overview of the main control loops is presented. The microgrid control strategies are classified into four control levels: local, secondary, central and global, where the first three levels are associated with the operation of the microgrid itself, and the fourth level demonstrates to the coordinated operation of the microgrid and neighbor grids as well as the main/host grid.**

***Keywords-Microgrid; hierarchical control; stability; renewable energy***

## I. Introduction

The microgrids (MGs) are small electrical distribution systems that interconnect multiple customers, distributed generators (DGs), and storage systems. The MGs are typically characterized by multipurpose electrical power services to communities that are connected via low voltage networks [1]. However, in order to allow seamless deployment of MGs, the relevant dynamic stability and control challenges should be solved. Compared to the conventional power systems with synchronous generators (SGs), the MGs with DGs and renewable energy sources (RESs) have either small or no inertia which is the main source of stability. With growing the penetration level of DGs/RESs, the negative impact of low inertia and damping effect on the MG dynamic performance and stability increases.

The MGs are known as the main building blocks of the future smart grids. The increasing penetration of renewable energy power into the power system among the MGs makes serious challenges in control design and operation and highlights the importance of these systems. Understanding the dynamics and using appropriate analytic methodologies are significant issues for MG stability analysis and control synthesis. Despite the small scale of a MG, it has many of the complexities of a large scale conventional power system. In conventional power grids, stability analysis is well established with standard models of SGs, governors and excitation systems of varying orders that are known to capture the important modes for particular classes of problems. This does not yet exist for the MGs and may be difficult to achieve because of the wide range of power technologies that might be deployed.

As an example, today, the massive use of power electronic converters for grid connection of generators, DC loads, HVDC power transmission leads to imagine in a near future the operation of electrical networks with no synchronous machines, i.e. with 100% power electronics penetration. As proposed in [2], MGs propose new high-level control strategies and management rules when operating, e.g. solutions to ensure system reliability (adequacy and security) when there is no longer a physical link between load/generation imbalance and the frequency in the electrical network. Since ancillary services are expected to be different in such a grid, high level management rules must also be adjusted.

Low inertia, uncertainties, dynamic modelling and stability, as well as bidirectional power flows issues are known as the most relevant challenges in MGs control and protection. On the other hand, DGs' output voltage and current control, active/reactive power balancing and frequency/voltage regulation, demand-side management, economic dispatch, and transition between operation modes are mentioned as the most desirable features of the MGs control system. Current efforts are mostly being put into the design of more effective control strategies and special protection schemes in different control levels that ensure stable, reliable, secure and economical operation of MGs in either grid-connected or islanded operation mode.

Control is one of the key enabling technologies for the deployment of future power systems. Various control loops must be used to improve the MGs stability and performance. The current, voltage/amplitude, frequency/angle, and active and reactive power are the main feedback variables used in the existing MG control loops in both grid-connected and islanded operation modes. Like conventional power grids, the MG has a hierarchical control structure with different operation layers. The hierarchical control structure of MGs are responsible to provide proper load sharing and DGs coordination, voltage/frequency regulation in both operating modes, MG resynchronization with the main grid, operating cost optimization, and power flow control between the MG, neighbourhood grids and the main grid.

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Advances in the MGs control improve the MGs potential to be integrated into the conventional electrical systems in a higher capacity. This improvement not only covers their internal control performance and connection/disconnection procedures in order to limit the negative dynamic impacts in the host network and other connected MGs, but also includes the grid support functionalities to enhance the global operation of distribution networks. Understanding the control concepts and coordination requirements to create smarter and more flexible distribution systems is underway. The problems related to achieving a smarter distribution system are new and performance objectives are still being explored. This paper provides an overall view on MG control hierarchical structure and understanding that have been extensively discussed in [2].

## II. MG HIERARCHICAL CONTROL

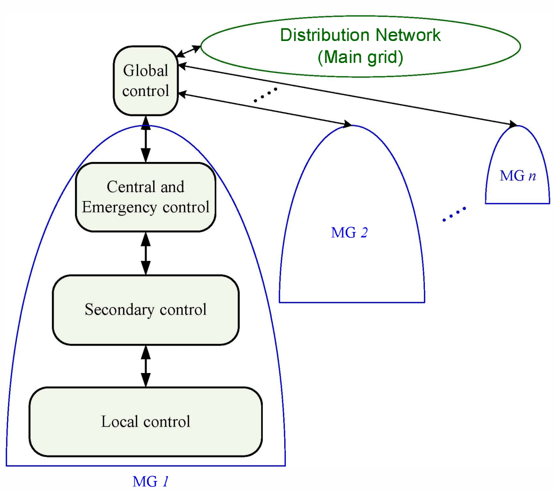


Figure 1. Hierarchical control levels in MGs [2].

Hierarchical control strategy for MGs consists of four levels, namely the *local* (primary), *secondary*, *central/emergency*, and *global* controls, as shown in Fig. 1. The *local control* that includes fundamental control hardware, comprises DGs internal voltage and current control loops, maintains DGs stability by measuring and controlling the local signals. It is essential to provide independent active and reactive power sharing controls and avoiding undesired circulating currents for the DGs/RESs using the available current, voltage and frequency feedback signals. The *secondary control* provides power sharing as a communication-based method for parallel configuration of DGs and compensates the voltage and frequency deviations caused by the load variation and local control operation. The *central/emergency control* level facilitates MG supervision activities, and its role is particularly important in the islanded operation mode. It operates as a MG energy management system (EMS) and monitors MG's local and secondary controllers. It is also responsible for islanding detection and connection/disconnection to/from the main grid, as well as emergency control and overall protection schemes. Finally, the *global control* manages the power flow between the given MG, other interconnecting MGs and the main grid, and facilitates an economically optimal operation. This level is working in the distribution network area, outside the MGs.

### A. Local Control

Local (also called primary or internal) control performs the first level in the control hierarchy, featuring the fastest response, and they are appeared in different forms depending on the type of DGs which can be addressed based on their technologies such as induction generators, synchronous generators, and power electronic Inverters/converters. In comparison of synchronous and induction generating units, the power electronic Inverters/converters provide more flexible operation.

The local controllers 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 the MG controls. The main usage of local controllers is to control DGs to operate in normal operation. Fig. 2 shows the local controllers for a DG which operates as a voltage-controlled voltage source converter (VSC), where the voltage reference is provided by the conventional droop controllers. Here, the droop controllers that are described in the next section are also working as local controllers. The nested voltage and frequency control loops in the voltage control mode are also shown in Fig. 2. This controller feeds the current signal as a feedforward term via a transfer function (e.g., virtual impedance which is introduced later). The LPF blocks show the *low pass filter* to provide active and reactive powers from the DG's output voltage and current signals.

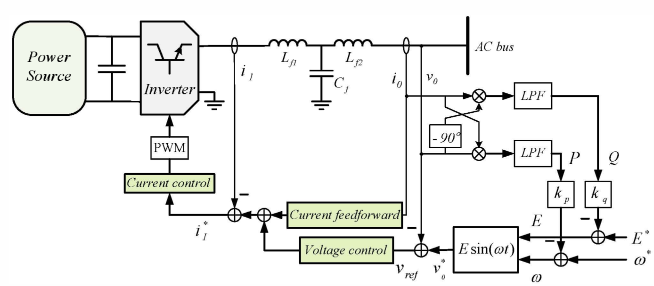


Figure 2. Local control loops in a voltage-controlled VSC-based DG [2].

The proportional integral (PI) controllers are widely used to the design of the control loops in the local control level. The PI controllers are used in the control loop alone or with additional feed-forward compensation to enhance the performance of closed-loop systems. This type of controllers is aimed to control operating points of the DGs and their power-electronic interfaces. Besides the primary voltage and frequency controls, DGs must control active and reactive powers. The droop-based active and reactive power controls are most common methods to control these powers. The $k_p$ and $k_q$ are constant droop parameters.

Like the DG's output control, the power sharing control between DGs could be also included in this level. DG's output control usually includes an inner and outer control loops for current and voltage regulation (Fig. 2), respectively. Power sharing control in a MG is responsible for the adequate share of active and reactive power mismatches. Both control functions can be performed by using primary active power-frequency and reactive power-voltage droops based on local measurement and without need for communication.

The local controllers design usually should be based on a detailed dynamic model of the DGs, 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. For the sake of modeling, stability analysis and local control synthesis in inverter based DGs, there are three reference frames: natural (*abc*), stationary ($\alpha\beta$), and synchronous ($dq$). The natural reference frame utilizes controllers realized with simple structure (e.g., PI), and is useful to time domain response analysis of the DGs and MGs. The stationary reference frame is mostly associated with sinusoidal variables, and finally, the synchronous reference frame is associated with DC variables and controllers.

### B. Secondary Control

Secondary control as second layer control loop complements 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. It is closely working with local and central control groups.

During the grid-connected operation mode, all the DGs and inverters in the MG use the grid electrical signals as references for voltage and frequency regulation. But, in islanding operation mode, the DGs lose the reference signal provided by the main grid. In this case they may coordinate to manage a simultaneously operation using single/multi-master operation methods. Secondary control also covers the control needs to improve the parallel operation performance for DGs (or inverters). There are many control techniques in the literature to make a successful parallel operation of DGs/inverters via master/slave, current/power sharing and generalized frequency/voltage droop control techniques [3].

Similar to the secondary control in conventional power systems, secondary controls in MGs are responsible to provide steady state voltage and frequency deviations in the presence of load changes and action of the local controllers in the islanded operation mode. For example, the voltage/frequency reference signals ( $E^*$ and $\omega^*$ ) in Fig. 2 are provided by secondary control loops. Secondary control operates on a slower time scale as compared to the local control. Improving the power quality for a set of DGs connected to a common bus [4] can be also considered as a secondary control loop. In contrary to the local control, in secondary control, it may need to use low bandwidth communications.

### C. Central Control

Central control referred to as the MG central energy management system (EMS) which is responsible for the reliable, secure and economical operation of the MG in either grid-connected or islanded operation mode. The main objectives of this control level consist of finding the optimal unit commitment (UC), reactive power supply and voltage and frequency control regulation (in coordination with secondary control), black-start restoration, and dispatch of the available DGs/RESs in normal conditions and performing load shedding and special protection schemes in off-normal and emergency conditions. Central control is the highest hierarchical control level inside the MG, which its role is more significant in the islanded operation mode. The central control can be also 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 MG central control (MGCC) as the MG supervisor.

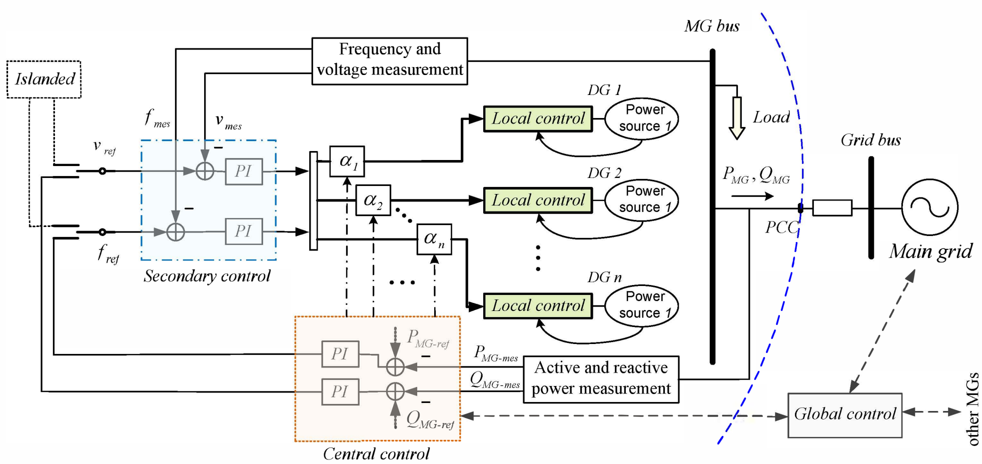


Figure 3. Local, secondary, central, and global controls [2].

Fig. 3 shows a block diagram showing the role and cooperation of local, secondary and central controls in the MG's frequency and voltage regulation. In case of supporting the main grid ancillary services by the MG, the global control also comes to play. As shown in Fig. 3, in the grid-connected mode, the power flow between MG and main grid can be managed by adjusting the amplitude and frequency of DGs voltages. First, the active and reactive output powers of the MG are measured. Then, these quantities are compared with the corresponding reference values to obtain the frequency and voltage references. These reference values are then used as the reference values to the secondary control.

The $\alpha_i$ is a *participation factor* of the *i*-th DG in the MG frequency or voltage regulation [5]. Following a load disturbance within the MG, the produced appropriate secondary control signal is distributed among DGs according to their participation rate, to compensate the generation-load imbalance. In a given MG, the sum of participation factors is equal to 1.

In addition to the constraints for the individual DGs, the whole MG should also take advantage of operating in islanded mode, during power outage, blackout, 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/or voltage of the islanded section of the network.

The islanding plan can be considered as most important emergency control scheme in the MG systems. When a MG system is islanded, the voltage/frequency might go beyond the power quality limits. In order to ensure system survival following islanding it is necessary to exploit controllable DGs, storage devices, local load as well as load shedding schemes and special protection plans in a cooperative way. The load shedding can be considered as an effective emergency control scheme in the MGs, which to be started following a significant drop in frequency and/or voltage.

In a 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. 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 central control loops.

In summary, the central/emergency controller is required to ensure that the MG operation is as seamless as possible during major disturbances such as transition between grid-connected and islanded operation modes. It is responsible for economic optimization of the MG in normal operation, as well as maintaining reliable, secure, and safe operation in emergency conditions. The central control level is also in charge of restoring the regulation reserve, managing eventual congestions, and giving support to the secondary control among the MG, if necessary.

### *D. Global Control*

The Global control is the highest level of control for coordinating the operation of multiple interconnected MGs, and communicating requirements with the main grid. For instance, coordination features for active/reactive power management of a grid consist of the main grid and interconnecting MGs could be accomplished by the global control. On the other hand, in the global control point of view, the MG can be controlled to interact with the distribution grid as a dispatchable and constant impedance load.

Global control deals with some overall responsibilities for a MG, such as interchange power with the main grid and/or other connected 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 neighbours similar to the existing supervisors for power exchanges and economic dispatch in a conventional multi-area power system. 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 balancing 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 control. Global control supervises 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 control performs an EMS for the MG to ensure a subset of basic functions such as load and weather forecasting, economic scheduling, security assessment, and demand side management.

In general, generation scheduling optimization, enhanced overall system control and dispatch services, energy imbalance compensation, and spinning reserve operation can be highlighted as the most significant objectives of the global control. The MGs can be also controlled in a coordinated way with the MGCCs to provide some ancillary services oriented to enhance the performance of the main grid.

In summary, the global control level is responsible for optimizing the MG operation and setting its interaction with the distribution network and neighbourhood MGs by controlling the active and reactive power references of DGs through the MGCCs. This optimization is usually based on economic criteria, which considers the demand-generation balance, together economic aspects. The MGCCs and global control level co-ordinately manage the exchange powers and some ancillary services.

## III. DROOP AND VIRTUAL IMPEDANCE CONTROLS

A simplified general representation for an inverter-based DG is shown in Fig. 4. In comparison to the conventional generators, the DGs such as natural gas and diesel generating units are very fast and can typically pick up load within 10-12 seconds from startup and can serve full load just a few seconds thereafter. The DG 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.

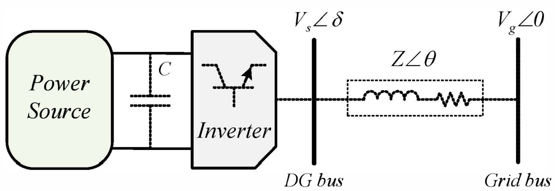


Figure 4. An inverter-based DG [2].

In the general grids, both inductive and resistive components should be considered. For this purpose, a rotation matrix T is required to transform the active and reactive powers (*P*, *Q*) into the rotational power components ( $P', Q'$ ) as described below:

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & -\sin(\varphi) \\ \sin(\varphi) & \cos(\varphi) \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \quad (1)$$

where, $\varphi = \frac{\pi}{2} - \theta$, and $\varphi$ is the rotation angle of matrix *T*. Thus,

$$P' = \frac{X}{Z} P - \frac{R}{Z} Q \quad (2)$$

$$Q' = \frac{R}{Z} P + \frac{X}{Z} Q \quad (3)$$

Assumed that $\delta$ takes a small value, the application of the rotation matrix results in

$$P' \approx -\frac{V_s}{Z} V_g \sin(\delta) \Rightarrow \delta \approx -\frac{ZP'}{V_s V_g} \quad (4)$$

$$Q' \approx \frac{V_s}{X}\left(V_s - V_g \cos(\delta)\right) \Rightarrow V_s - V_g \approx \frac{ZQ'}{V_s} \quad (5)$$

where, $P'$ and $Q'$ are the rotated components of *P* and *Q*. From (4) and (5), it can be seen that regulating the rotated active power $P'$ and reactive power $Q'$ control the angle $\delta$ and voltage deviation $\Delta v$ , respectively. Therefore, in a general case, the droop control equations can be written as follows:

$$f - f_0 = -k_p(P' - P'_0) = -k_p \frac{X}{Z}(P - P_0) + k_q \frac{R}{Z}(Q - Q_0) \quad (6)$$

$$v - v_0 = -k_q(Q' - Q'_0) = -k_p \frac{R}{Z}(P - P_0) + k_q \frac{X}{Z}(Q - Q_0) \quad (7)$$

Equations (6) and (7) show that by changing the values $k_p$ and $k_q$ in a MG, the system frequency and voltage amplitude can be controlled. This fact is examined in the next subsection. Then, from above equations one can obtain a *general droop control* (GDC) relationship []. Fig. 5 shows an example of an inverter-based DG (working as a VSI unit) for supplying a local load through a line. The LCL output filter has been added to prevent the resonance impact in the output network. Also, the LCL damps the distortion of output sinusoidal waveform and reduces high frequency harmonics caused by switching operations of the VSI. Therefore, it is used in the inverter output for the quality of output current and bus voltage in the context of weak grids [6].

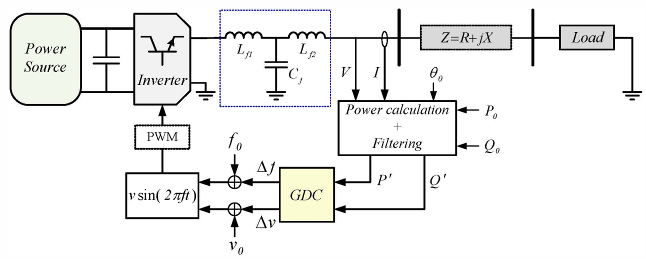


Figure 5. An example for GDC-based droop control [2].

As mentioned, the performance of a droop control system in a MG is highly dependent on the grid impedance parameters, specifically in the general case. A small mismatching in the grid impedance estimation results in an inefficient power sharing among the droop controlled DGs. Therefore, the application of droop control in all kind of MGs, without using of a sophisticated grid impedance estimation mechanism to calculate the line parameters or the rotation matrix *T* (1) may not be effective [7].

In order to solve this problem, several solutions are introduced to decrease the dependency of the conventional droop controller performance on the line impedance parameters, over the years. Using a large inductor between the power converter and the AC bus to make an inductive line impedance, is one of these solutions. However, due to reduction of the overall efficiency and increasing the size and the costs, this solution does not provide an efficient methodology. Application of intelligent algorithms such as artificial neural network (ANN) and adaptive neuro-fuzzy system to estimate the line parameters and to cope the rotation matrix can be considered as another class of solutions. A simple but effective solution consists on updating the power converter control loop by virtually emulating the effect of an inductive element in the link impedance. This concept is known as *virtual impedance*, and has been successfully implemented for regulating the power sharing among parallelized inverters and limiting over currents under grid disturbances [8].

The virtual impedance updates the power converter output voltage reference, where the new voltage reference is obtained by subtracting the virtual voltage drop across the virtual impedance from the reference value originally provided by the droop equations [9].

$$v^*_{ref} = v_{ref} - v^*_g = v_{ref} - Z_V i_g \quad (8)$$

The transfer function of virtual impedance block $Z_V(s)$ must be selected according to the nominal power of the converter. An example of the implementation of the virtual impedance concept in a grid-connected power converter (working with *P*-*Q* droop control method) is shown in Fig. 6.

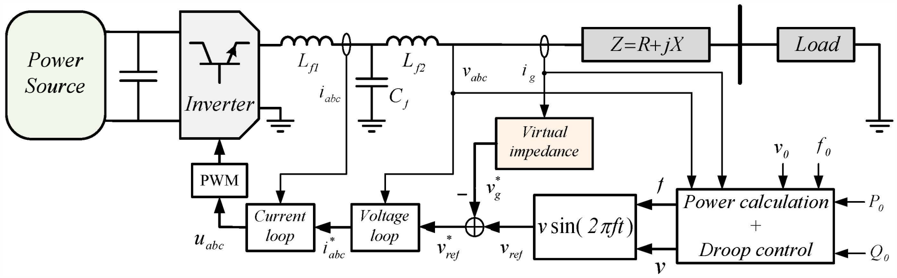


Figure 6. A power converter with virtual output impedance loop [2].

## IV. CONCLUSION

This paper presents an overview of the control levels and existing control technologies and challenges in MGs. The MG's hierarchical control structure is determined by four control levels: local, secondary, central, and global controls. The local control deals with the each DG's internal voltage/frequency and current control loops, while the secondary control covers a higher level control loops such as the voltage and frequency control among a bus connecting a set of DGs or MG following a load variation. The central/emergency control operates as a MG energy management system and it is responsible for emergency control and overall protection schemes. The global control supervises the power flow between the given MG, other interconnecting MGs and the main grid, in an economic optimal operation. Finally, droop characteristic in inverter-based DGs as well as virtual impedance concept are addressed.

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