

An Overview on Microgrid Control Strategies

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Abstract—In response to the ever increasing energy demand, integrating distributed energy resource-based microgrid will be the most promising power system improvement in the near future. Microgrid system implementation provides significant advantages for both electric utility provider and end customer user. This paper performs a comprehensive literature review on the current key issues on control strategies of microgrid islanded mode operation. Brief descriptions are provided for typical microgrid control methods, PQ control, droop control, voltage/frequency control, and current control, which are associated with microgrid mode of operation. This review also covers microgrid control issues such as islanded mode, stability, and unbalanced voltages to provide adequate power quality. In addition, this paper discusses the challenges of microgrid islanded mode issues, such as load sharing, distributed generation losses, and non-linear/unbalanced load. Finally, research conclusions of the important microgrid control requirements for future development are also described.

Index Terms—Microgrid control, microgrid structure, microgrid issues.

I. INTRODUCTION

The main factors that make using distributed generation resources interesting are reducing the emissions of CO₂ and recent technological developments in micro generation domain [1]. Microgrid is the future of efficient and fast restoration of power systems. Microgrid allows the high penetration of distributed generation into the power systems. Several benefits of microgrids include facilitating distributed generation (DG) and allowing high penetration of renewable energy sources. Moreover, microgrids provide local voltage and frequency regulation support and improve reliability and power capacity of the grid [2]–[4]. Control strategies and issues closely related to microgrid operation have been explored in previous studies. The most popular among the control strategies based on droop characteristics has been controlled in [5]. In addition, a central controller is described in [6] within a hierarchical control scheme to optimize the operation of the microgrid during interconnected operation. In [7], an advanced sliding mode controller based on stability function is considered to discuss and design a suitable mathematical modeling with uncertain parameters to enhance the dynamics characteristics of microgrid. Conventional control strategies can be applied to counteract stability issues [8]–[12].

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However, given the presence of varying stability issues, control strategies specific to each issue should be developed [13]–[16]. Affected parameters such as voltage and frequency need to be identified [17]–[21]. The rest of this paper is organized as follows. The microgrid structure is presented in Section 2. Microgrid control methods, including PQ control, droop control, voltage/frequency control, and current control methods, are formulated in Section 3. Section 4 discusses microgrid control issues. Finally, conclusions are drawn in Section 5.

II. MICROGRID STRUCTURE

A microgrid power system [22] is a small-scale power supply network designed to provide power for a small community (Fig.1). Microgrid technology has been attracting increasing interest in research and development phase in the last decade. A major advantage of microgrid is its ability to work alone during the utility grid disturbance or outage. Microgrid can operate in two modes, namely, islanded mode and grid-connected mode. In islanded mode, the microgrid disconnects itself from the main grid and operates autonomously during disturbances, maintaining high-quality service without harming the integrity of transmission grid. In grid-connected mode, the microgrid is connected to the main grid and enables bidirectional power flow [23], [24].

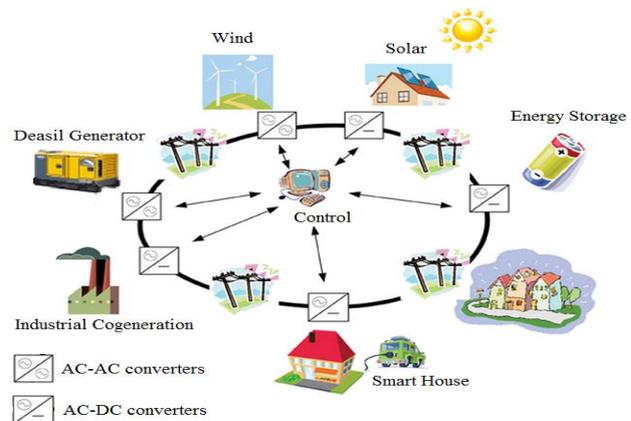


Fig. 1: A typical Microgrid

The main components of microgrid contain multiple distributed energy resources, such as wind turbines and solar panels; local loads, such as commercial and residential; and energy storages, such as batteries and flywheels. The challenges of microgrid include integrating all energy sources, operating in a stable and reliable condition, and managing the imbalance between loads and generations. The microgrid can optimize the aggregate distribution system by coordinating the generation and load to increase the robustness and reliability of the system in both modes of operation [25].

III. MICROGRID CONTROL METHODS

Microgrid technologies can be classified into two modes of operation, namely, grid-connected mode or islanded mode. Using microgrid control system has two advantages. One is that the stability of microgrid operation in frequency and voltage is maintained, especially in the load changes or interconnection with other networks [26]. The other one is that the active and reactive powers of the converter are regulated. The current survey will consider PQ control, droop control, voltage/frequency control, and current control methods.

A. PQ Control

In microgrid systems, a public control is used, which is called PQ strategy. PQ controls the voltage output of the inverter by injecting the active and reactive powers. This control is used in cases wherein the microgrid is not required or unable to provide voltage or frequency support as a current-controlled voltage source [27]. With PQ control, the microgrid controller does not change the output settings of its microgrid in response to fluctuations in terminal voltage or frequency [28], which requires a reference frequency signal to operate. During grid-connected operation, this reference frequency is supplied by the main grid. Meanwhile, in islanded operation, this reference frequency has to be supplied by another microgrid that operates on droop control.

B. Droop Control

Droop control method is used in conventional generators of power plants. In islanded operation of converter-based DG systems, this method can be adopted to share total load and control voltage magnitude and frequency in a special range. In this control unit, active power of total load can be shared among sources by drooping the frequency as a function of output active power of converter [29]. The applicability of droop control is readily apparent by considering the relationships that dictate the power transfer in a two-inverter system (Fig. 2).

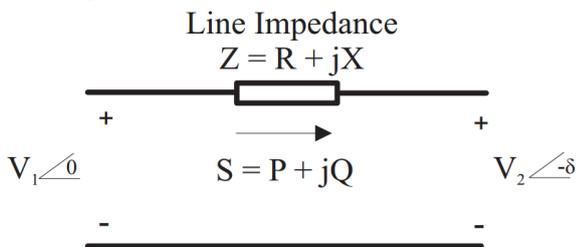


Fig. 2: A system with two voltage sources [30]

Conventional droop control is based on several assumptions such as the output impedance having negligible effect on the power characteristic (output impedance is small compared with line impedance) and no cross coupling occurs in the P- ω or Q-V relationships. These assumptions can significantly influence the appropriate control law. One way to address these issues is by applying a linear rotational transformation matrix and modifying the control law. The linear rotational transformation is applied as follows [31]:

$$\begin{pmatrix} P' \\ Q' \end{pmatrix} = \begin{pmatrix} \sin(\theta) & -\cos(\theta) \\ \cos(\theta) & \sin(\theta) \end{pmatrix} \begin{pmatrix} P \\ Q \end{pmatrix} \quad (1)$$

Notably, the power transfer relation is expressed in terms of phase and voltage differences, whereas droop relies on frequency and voltage differences to transfer power. This phenomenon is because the frequency difference will periodically change by a small amount. The wandering droop

frequency results in a constant phase difference that is necessary to transfer power. The droop frequency for a constant phase difference may be found by solving:

$$\phi = (\omega_o - \omega)t \pmod{2\pi} \quad (2)$$

Certain fundamental limitations on the power may be transferred between the two systems.

$$P = \frac{V_2}{Z} [(V_1 \cos(\delta) - V_2) \cos(\theta) + V_1 \sin(\theta) \sin(\delta)] \quad (3)$$

$$Q = \frac{V_2}{Z} [V_1 (\cos(\delta) - V_2) \sin(\theta) + V_1 \cos(\theta) \sin(\delta)] \quad (4)$$

Where $\theta = \tan^{-1}(X/R)$ is the angle of complex line impedance.

Most inverters operating with droop control need an inductive filter, which could be in series with inverter output and microgrid. The primary purpose of the inductor is to filter the switching frequency components from the output. The impedance of the inductor is usually significantly small. Thus, low order harmonics result in harmonic currents as follows:

$$I_k = \frac{V_k - V_{INV}}{j\omega_k L_{limk}} \quad (5)$$

Where V_k and I_k are the k^{th} harmonic of the grid voltage and harmonic current, respectively. Another solution is increasing the output impedance at harmonic frequencies. This approach is conducted by lowering the output voltage at harmonic frequencies in proportion to harmonic currents, that is, lower V_k/I_k , k in the integers. This functionality may be combined with the voltage feed-forward (Fig. 3). Other issues encountered with traditional droop control include slow phase response time and poor damping. These issues are addressed using phase feed-forward, which lowers the transient time of the phase response given that the feed-forward path is in parallel with an integrator [32]–[34] and impedance feed-forward, which lowers the output voltage in proportion to the output current. This phenomenon increases the apparent output resistance and damping in the system.

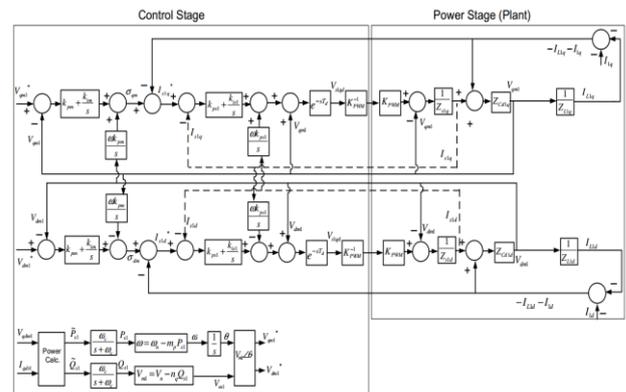


Fig. 3: Droop control [32]

C. Voltage/Frequency Control

The microgrid voltage control ensures that the voltage remains within the set point values by adjusting generated or consumed reactive power [35]. A voltage controller is designed with the terminal voltages as input and compared with the reference voltage. The error voltage is filtered using a low pass filter and multiplied by a gain constant to obtain droop control of the voltage source converter.



The output of the voltage regulation control block gives the reactive power that needs to be injected to maintain the terminal voltage according to droop set value [36]. Hence, the traditional frequency droop control through active power and voltage droop control through reactive power may not function very well on low-voltage network-based microgrid. Thus, the voltage control should be implemented through active power and frequency control through reactive power generated in an inverter [37]. The inverter of the PV array consists of two major control loops, namely, the reactive power control and the DC voltage control (control of active power). A control scheme is proposed to maintain frequency and voltage during islanded mode in microgrid with wind turbine, photovoltaic system, and battery inverter [38]. A power system level MVAR controller is designed, which issues reference VAR commands over the communication channel to each microgrid controllable asset controller. Then, the microgrid controller regulates the VARs locally in each component to obtain the desired voltage and VAR output at the grid connecting feeder.

Proper voltage controllers are required to avoid the collapse of voltage. Conventional power grid has high (X/R) ratio, that is, the grid is predominantly inductive. In such system, reactive power cannot be transported over long electrical distances because of the drop in terminal voltage. However, given that the electrical distances are relatively small in a microgrid, the reactive power can be transported from generators to the loads without a significant drop in the voltage. The voltage at a bus in any system is an important operating parameter, which is required to be within certain limits. Various disturbances, such as line outages, load switching, and line faults, lead to a drop in voltage at buses. In the present power system, when a large reactive load switches into the system, the consumer is required to notify the utility to install reactive power compensator(s) at the consumer site. However, the electrical distances between the sources and loads are small in a microgrid. Thus, the reactive power can be transported from the source to the load directly. A novel microgrid voltage stabilizer (MGVS) is proposed in [39]. This stabilizer can be used to coordinate the consumption of reactive power in a microgrid system. The MGVS is based on the inputs from load buses, runs a subroutine, and gives a signal to the DGs to kick in the reactive power to support the new reactive load that switches into the microgrid system. When the microgrid is in islanded mode, the voltages at the load buses drop. In this case, the MGVS can function as a fast acting voltage controller by sensing the voltage drop immediately and pushing the distributed generators to generate more active and reactive powers. During short circuit faults, large currents flow from generator buses to the faulted load buses. Therefore, the MGVS can help the microgrid to use the reserved reactive power efficiently and improve the dynamic voltage stability. Meanwhile, the microgrid frequency control keeps the frequency of the microgrid around the set point value. In a large power system, the generators have storage in their inertia. Therefore, when a new load comes into the system, the frequency decreases slightly and the generator supports the load during the dynamic state. Meanwhile, distributed generators have slow response and are almost inertia-less. Therefore, designing a microgrid along with the frequency controllers to provide some storage is important [40]. Power

versus frequency drop characteristics vary depending on the nature of the DG and one of the critical microgrid performance curves. At the instant of islanding, the voltage phase angles at DG buses change, resulting in an apparent reduction in local frequency. This drop in frequencies of the DGs forces them to raise their power output and share the load proportionally [41]. A dynamic analysis of generation control scheme consisting of active power-frequency and reactive power-voltage controllers for the inverter-based DGs is presented. In addition, guidelines are provided for the design of active power-frequency and reactive power-voltage controllers. Fast and accurate voltage and frequency control are essential requirements for successful islanding operation of weak low-voltage network-based microgrid. To manage with the fast changing frequency and voltage in normal range, the microgrid should include one relatively large capacity inverter-based energy storage unit, which would address this rapid control [42]. A microgrid with synchronous machine and an electronically interfaced DG unit can maintain the angle stability even after most severe islanding transients, primarily through its fast real power control. In addition, such system can enhance voltage quality at specific buses, mainly through its fast reactive power control. In the absence of synchronous machines, inverters are responsible for maintaining and controlling the frequency of the microgrid [43]. A small-signal state-space model of autonomous operation of inverter-based microgrid is presented in [44]. In this model, each distributed generation inverter has an outer power loop based on the droop control to share the real and reactive powers with other distributed generations. Voltage and current controllers are also used in inverter controls to reject high-frequency disturbances and damp the output filter to prevent any resonance with external network.

D. Current Control

Current mode control (CMC) (Fig. 4) is typically used to track the set point derived from droop or other control approaches. Notably, in this control approach, both loops have finite gain, the inner (current) loop acts as a disturbance that introduces a voltage and phase offset proportional to load current. Therefore, changes in the load impedance will change the system transfer function, thereby changing the amplitude and phase at a given frequency. This phenomenon is apparent from the system transfer function expressed in [45]:

$$T = \frac{Z_L \cdot Y_{link} \cdot K_{inv} \cdot K_{cont}}{Z_L \cdot Y_{link} \cdot K_{inv} \cdot K_{cont} + Y_{link} \cdot K_{inv} \cdot R_i + Z_L \cdot Y_{link} + 1} \quad (6)$$

Current mode control has been shown to have better dynamic response and tracking compared with the basic droop approach. Current mode control also has inherent line feed-forward and current limit. This method has been successfully used as the control strategy in parallel inverters. Two fundamental issues with nested control loops are instability because of simultaneous perturbations and uncertainty. Both of these issues are addressed by designing a μ -controller, which can be used to guarantee robust stability over all specified values of uncertainty [46], [47]. Given that uncertainty bounds may be specified for μ -controllers, the load may be specified as an uncertainty.



The resulting controller would allow the use of the inverter as long as the load is within the specified range. The current sharing ability of inverters with CMC may be considered. The difference in currents is also referred to as circulating current. If these equations and the impedance “seen” by each inverter are considered, then the difference in line impedances playing an important role in current sharing becomes apparent. At this point, the output impedance of each inverter maybe considered. The output impedance of an inverter is typically ignored and the line impedance is considered. However, the output impedance is considered to be in series with the impedances and represented as z_1 and z_2 (Fig. 5).

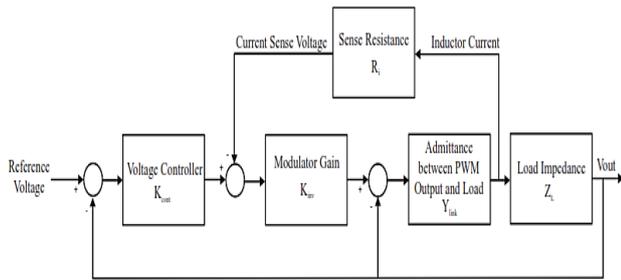


Fig. 4: Two loop (current mode) control with inductor feedback [45]

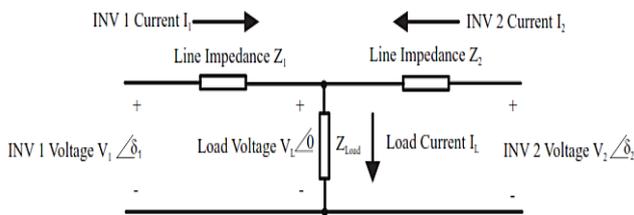


Fig. 5: Current sharing for inverter [46]

IV. MICROGRID CONTROL ISSUES

A. Islanded Mode

During islanded operation, storage devices and load-shedding technique have major functions to avoid large frequency deviations. A control strategy for voltage, frequency, and protection during microgrid islanding is defined in [48], [49]. Voltage, frequency, and protection control strategies were initially defined separately. Then, the control strategies were coordinated by using an islanding detection algorithm to improve the response of the overall system. In addition, a black start procedure within islanded mode including DGs has been developed [50], [51] to increase the reliability of the microgrid. Moreover, the PQ inverter controls the active and reactive powers set point. Furthermore, the VSI control maintains the voltage and frequency set point. The input to PQ controller is the loading conditions of the system. This controller is also responsible for load shedding, if generation and demand are mismatched. The VSI controller acts as a synchronous machine in a power system to the microgrid by giving the required voltage and frequency reference. The following issues usually occur within the islanded mode: Firstly, when the DGs supply all the load demand within the microgrid, a proper sharing is necessary. However, considering the presence of DGs of unequal capacity, uniform load sharing is impossible. Therefore, the total load is shared in proportion to the capacity of each source [52]. Apart from the normal load

sharing, the DGs need to share harmonic current and the compensation efforts for load unbalance and non-linearity. Meanwhile, given the difference in the line impedance, the output voltage of the inverters is different from each other. This phenomenon makes sharing the reactive power equally without a steady state error difficult [53]. Furthermore, the inverters supply excess reactive current to compensate the error in reactive power sharing, which suffers from reduced capacity to supply active power. Secondly, the loss of a DG in isolated microgrid allows exploring the scope of using an advanced load shedding, smart loads, and battery unit that can keep the critical loads running even under severe power outages. A few control challenges that are commonly faced using either load shedding or smart load methods are as follows:

- If the fault is unclear within the critical clearance time, the wind turbine in the microgrid can trip, resulting in more power shortage in the microgrid. This phenomenon requires the load shedding or the smart load method to act fast.
- Load shedding has to be conducted in proper stages by optimal disconnection of less critical loads, with switching points lying in a hysteresis band to avoid oscillations [54].
- Microgrids consisting of a synchronous generator can suffer from voltage instability because of heavy load shedding. This phenomenon is caused by the excess generation of reactive power by the synchronous generator to stabilize voltage in response to the sudden load shedding [55].
- With a large power shortage or presence of a huge load, the smart load control fails to stabilize the frequency of the isolated microgrid and results in frequency decay.

Third, the presence of non-linear load or unbalanced makes ensuring stability in an islanded microgrid more challenging. A few control challenges are listed as follows:

- The presence of unbalanced loads result in second order harmonic component in the load current, which distorts the DG/MS output voltages. The non-linear load results in higher order harmonics. Hence, current and voltage are more distorted. In these scenarios, normal voltage and frequency regulation schemes are ineffective. Therefore, a control scheme that can maintain the stability of the system without removing the unbalanced and non-linear loads from the network is required [56].
- Low-frequency variations of the DG output also vary the distorted load currents, thereby making tracking and stabilizing more difficult.
- The conventional method of using negative sequence current for voltage unbalance compensation only addresses the voltage unbalance at the DG terminal. Meanwhile, unbalance compensation at the load bus is more important because all the sensitive loads are connected to it [57].

- With droop control, DG units supply sinusoidal voltage with fundamental frequency, which can form a short circuit path for harmonic current. This phenomenon results in an improper sharing of harmonic current among the DGs. Therefore, the DG in close proximity to the unbalanced load supplies the highest harmonic current, thereby reducing its capacity to supply other loads [58].

B. Stability

Microgrid stability issues may arise from various causes, such as islanding and reconnection to the grid, different types of faults, changes in network parameters, mismatch in the power generation demand, and sudden connection or disconnection of DGs or loads in the system. With these issues, over or under voltages and frequencies may occur [59]. Therefore, considerable research works were conducted to develop voltage controllers, frequency controllers, and schemes of islanding operation or reconnection [60], [61]. In addition, power electronic-based DGs provide flexibility to the microgrid control. Connecting the distributed generation sources to the electrical network has various major challenges. These barriers include technical issues, business practices, and regulatory issues.

C. Unbalanced Voltages

In a three-phase power system, the phase voltages are imperfectly sinusoidal in nature and have some degree of unbalance. Therefore, a microgrid needs to be designed to operate under unbalanced conditions. The voltage unbalance occurs because of various reasons such as the spacing of the overhead transmission lines, three-phase loads with unbalanced impedances, and a fault in the power system. Voltage unbalance can be defined as unequal voltage magnitudes at fundamental system frequency (under voltages and over voltages), fundamental phase angle deviation, and unequal levels of harmonic distortion between the phases [62]. Most literature works consider microgrids as a balanced system and very few papers have addressed the problems regarding unbalanced conditions. As mentioned previously, unbalanced load is the main contributor to unbalanced voltages. Proper voltage balancing techniques, such as feeder switching operations, can distribute the load among the three phases. Distribution transformers with balanced impedances can also remove voltage unbalances. Voltage unbalance compensation can also be achieved by using passive power filters or power electronic devices [63]. Thus, uncontrolled excess generation results in distortion of the voltage profile of the islanded microgrid. The following control strategies are recommended to overcome these challenges:

- The characteristic difference between the DGs (PV and wind turbine) in the microgrid is necessary to develop different control strategies to regulate their maximum output power injected into the network.
- In scenarios wherein the AC loads, DC loads, and storage units are unable to consume the active power produced by the DG units, a power oscillation can be developed in the islanded microgrid.

V. CONCLUSION

This paper presented a comprehensive overview of microgrid control strategies. The current key issues of technical challenges especially in the microgrid control methods and its control issues are introduced. These challenges can be

addressed by collecting the information for an optimal performance from the microgrid controller and the load conditions. However, a good control strategy is required to manage the power from each DG while optimizing the use of renewable energy sources and meeting the energy demand of all loads. Several research challenges need to be solved in the future to support the integration of the microgrid with utility network, such as obtaining information about energy demand of the load without any communication with the microgrid center controller. Meanwhile, the multi resources within a microgrid can be controlled by using multi object controllers, which can be divided into number of controllers, such as voltage, frequency, and current controls.

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