

# Microgrid System

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## Abstract

Due to the growing awareness of the harmful impact of conventional fossil fuels and advancements in renewable energy technologies, microgrid has grown in popularity. This chapter aims to provide holistic learning of the microgrid system. This chapter is not only helpful for readers who are new to the world microgrid energy systems but also provide essential information to experts of this field. The chapter highlights the need and merits of adoption of microgrid systems while also highlighting the barriers in its implementation. The chapter also provides the various methods of categorization of microgrid while also emphasizing critical points of multiple categories. The different aspect of the deployment of microgrids such as its architecture, mode of operations, control strategies, monitoring methods, protection schemes, and energy management strategies are categorically explained. The fundamental requirement of the protection system and its functions are described to provide the overview of protection schemes used in the microgrid in this chapter. Various protection schemes will be discussed in the other following chapter giving more emphasis on new protection strategies.

**Keywords:** active distribution, passive distribution, central controller, control system, protection, differential protection, relaying, microgrid, renewable energy sources.

# 1. Introduction

## 1.1. General overview

The energy demand has increased due to industrial development, population increase, and other issues in recent years. Energy crisis due to the increased demand is considered a significant problem in the world. Due to an imbalance in the electricity supply market and generation of electrical energy along with faults in the system leads to a large number of outages and blackouts in the grid all around the world which impact on the economy as well as social life [1]. Conventional power grids and generation power station are not able to meet the increasing energy demands. Also, the rising fuel cost, environmental pollution is considered as another disadvantage of the traditional power generation plants. Because of these several problems forced the governments and other private agencies all over the world to increase the penetration of Renewable Energy Source (RES) in the power grid to meet the rising energy demands. The wind and solar is most reliable of all other RES and considered as the primary source of electricity generation in many countries. The low power generation capacity of RES has motivated to combine different types of electricity generating to form more sustainable microgrid. Microgrid has more power generation capacity and reliability supplying local loads as well as possible integration with the conventional grid [2]. Nowadays, with an increase in RES penetration and technological development of efficient solar panel, wind power generation technology, the microgrid is one of the prominent solutions to the problem of depleting fossil fuel resources in traditional power generation. Power generation from fossil fuels having several environmental issues and low energy generation efficiency. RES is a potential solution to the problems of meeting load demand, reducing dependency on depleting fossil fuels, reducing carbon emission thus reducing pollution and other environmental benefits as well as human health benefits [3].

A microgrid is a single structure composed of RES, loads, Energy Storage System (ESS), control system or central controller and protection system. Based on power generation and load nature of power consumption, the microgrid is either AC or DC forming load grid to connect loads, RES generators, battery energy storage system and possible interface with local utility network via the bi-directional converter system. The AC microgrid is more or less similar to the conventional AC power network, and research in this area has advanced comprehensively. In recent times, the advantage of DC microgrid gained the attention of the study due to its benefits and fewer conversion losses to deliver DC power using a cable system. Moreover, DC transmission system is inherently efficient, no skin effect and have fewer transmission losses. With the research and development in the area of the microgrid, it has three categories as DC microgrid, AC microgrid, and hybrid microgrid architecture. The microgrid has three layers in its structure namely distribution layer, central control layer and individual RES control layer. Microgrid has two operation mode which is grid-connected mode and islanded mode of operation. Microgrid has several control modes; some best control modes are master-slave control mode, peer-to-peer mode, combined mode, inverter control mode, etc. This chapter is more focused on establishing the fundamentals of microgrid and an overview of its challenges.

## 1.2. Classification of microgrid

Microgrids are classified based on its generation capacity, type of installation and load, structure and connection to the grid. Table I show the classification of the microgrid based on its installed capacity. Based on installation and load the microgrid caters, it is classified as military grade microgrid, campus microgrid, community microgrid, Island microgrid, and

remote microgrid. Based on the nature of supply system microgrid adopts and the common bus it makes inside the structure, the microgrid is classified into three types which are shown in Fig. 1. Each unit in Fig.1 of the microgrid structure has a power controller (maximum power point tracking), a circuit breaker to disconnect in even of severe disturbances and appropriate communication protocols. In remote type microgrid, the AC structure is very suitable to supply local load while for Universities or organizations (campus microgrid) DC type microgrid is more ideal for heating purposes and military & corporate microgrid; the hybrid structure is more preferred to maintain the reliability, minimization of losses and supply DC loads. Based on the connection to the grid, the microgrid is classified as large grid-connected microgrid and small grid-connected microgrid. Some other general classification can also be done based on the number of supply phases, voltage levels, etc.

Table I. generation capacity based microgrid classification

Capacity (MW)	Type
< 2	Simple microgrid
2-5	Corporate microgrid
5-20	Feeder microgrid
> 20	Substation microgrid

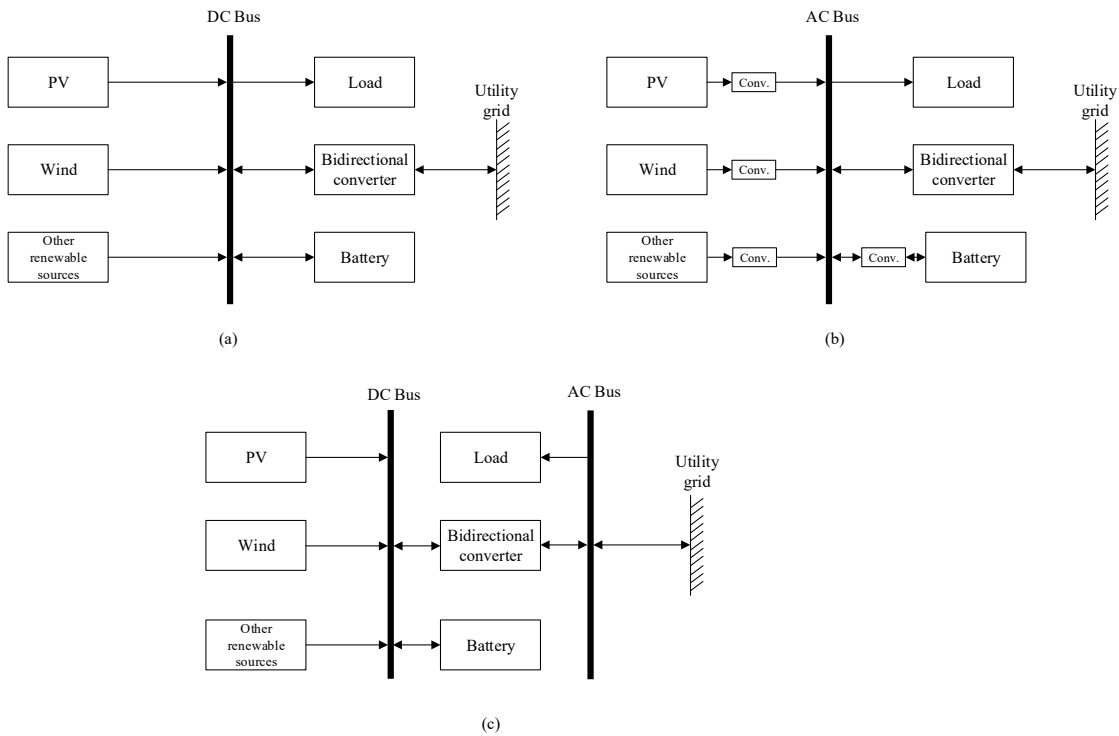


Fig. 1. Microgrid classification based on structure (a) DC microgrid (b) AC microgrid (c) AC/DC Hybrid microgrid

Technological, environmental and social advantages of microgrid make it highly preferable for supplying power in the remote/rural area, independent organization and also to the national grid. However, to accomplish a stable, reliable and secure microgrid grid operation, numerous technical, regulatory, social and economic issues should be addressed before making microgrid a conventional [3]. Some areas that would require more attention are irregular and weather-dependent power generation from RESs, low energy harvesting, and efficiency, lack of suitable standards and grid connection code for the microgrid. The research on these issues is taken up

by leading engineering and research organization/institute across the globe by conducting extensive real-time and off-line microgrid technology research.

### 1.3. Advantages of Microgrid in power distribution network

Microgrid development and integration in the utility is hopeful for the traditional power distribution network and have the following advantages:

- 1) **Environmental benefits:** in comparison to conventional power generation (thermal-coal based), microgrid based on renewables have a lesser and negligible impact on the environment [4]. The energy harvested from renewables helps to reduce greenhouse gas emission, pollution reduction, particulate matters and harmful gases reduction in air, improvement in air quality, no waste production. The carbon and greenhouse gas emission is contributing to global temperature rise, and widespread deployment of the microgrid will help in the reduction of global temperature [5]. RES based microgrid has significant environmental benefits, and with currently available technology, it is feasible to deploy microgrid to save earth's environment for a future generation [6].
- 2) **Operational benefits:** microgrid is installed at the load, and it reduces the utility transmission & distribution losses hence save the energy wastage. It improves voltage profile providing local reactive power support. Improves reliability to supply critical loads and therefore helps in maintaining continuity of power supply. Reduction in investment for transmission and distribution network expansions. Microgrid supply surplus power to utility and helps in power system stability improvement. Microgrid participates in ancillary services to improve overall system security.
- 3) **Power quality benefits:** enhancement in power quality of supply due to decentralization, a better balance between generation and load demand, reduction in power outages from utility-side, system downtime reduction and improves restoration of the power system.
- 4) **Human development index benefits:** energy access to all helps in the improvement in human development indexes such as [7-11] (a) energy access for clean cooking and lighting purpose can immensely improve the household air quality and thus providing a better healthy condition to women and children which can lead to a significant reduction in premature deaths (b) the energy needs for the medical and health sectors specifically in developing economies is sure to rise individually for having better-equipped hospitals and storage units for vaccines (c) access to modern, economical and reliable energy services can undoubtedly improve the women's wellbeing and could also provide them with new economic opportunities (d) girls with better electricity access in rural areas are more likely to complete their school education by the age of 18, and also self-employed women with better electricity access are expected to generate more income as compared to ones without access [7] (e) proper access to energy in the agriculture sector in a rural developing area where animal and human power acts as a primary energy source for farming purposes, the yield, and productive uses can be improved significantly (f) reliable and economical electricity access can help entrepreneurs to start and grow business enterprises which can provide services to the sectors and communities that add towards economic development and well-being (g) better energy access helps in reducing poverty and income opportunities which also improves gender equality in developing nations (h) better energy access can help in

avoiding the high levels of food losses with better processing and storage units and thereby reducing hunger and poverty (i) helps to achieve development goals and support expanding economy in developing nations providing surplus energy generation.

#### **1.4. Challenges in microgrid project development**

The microgrid energy system based on RES has been entirely transformed from a simple system to a more complex system due to the inclusion of multiple benchmarks, stakeholders, and disagreeing aims [4-11]. Moreover, to achieve widespread integration of RESs in the present electrical energy system scenario thoughtful consideration should be given in planning and execution considering economic, technical, social, environmental as well as institutional hurdles [12]. The next significant barriers/hurdles remain in the successful deployment, and implementation of renewable microgrids for rural electrification in developing nations are:

- 1) **Socio-cultural:** Social factors play a crucial role in electrification projects in developing areas. Public acceptance is one of the significant barriers to the successful implementation of energy projects. The participation and view of local communities help in deciding possible energy alternative for their needs. The chances of failure occur whenever the people views are ignored which make them feel isolated and sometimes endangered by it. In the majority of cases, lack of public acceptance has direct implications on microgrid projects based on renewables which also results to higher upfront cost, delays due to frequent protests against the plans and sometimes termination of the energy projects. Other social factors are closely interconnected to community acceptance which are more of traditional and cultural traits, health, economic benefits from projects, etc. Many times due to lack of awareness and primary energy education, community populace do not want to use the advanced energy services often thinking it as an economic burden to their livelihood and thereby opposing the microgrid projects in developing nations.
- 2) **Economic:** microgrid electrification projects based on renewables requires a higher upfront capital cost investment which in turns leads to a higher cost of generation as compared to the energy projects based on the conventional energy sources. The one closely related factor connected to the higher capital cost of renewable energy based projects is not giving thoughtful consideration towards the selection and development of microgrids based on least-cost energy resource first. Some other financial obstacles include the absence of sufficient long-term funding prospects which in turn can support the products for renewables. There is often a case of a disparity between the term of supporting funds and the cash flow of the microgrid projects. Moreover, financial security and return on investments in energy projects based on the renewables are also questionable. Market constraints such as inconsistency and uneven pricing of renewable products, information irregularities, misrepresentation in power market, indigenous underdeveloped renewable industrial chain, etc. and trade barriers such as imposing heavy import duty taxes which makes the renewable products quite expensive adds up to the economic obstacles.
- 3) **Environmental:** Zoning regulations and environmental features (harsh climatic condition and tougher geographical terrain) can hinder the deployment of microgrid

project in specific areas. Land requirements and its acquisition are also one of the significant obstacles for microgrids based on the wind, hydropower, solar photovoltaics, etc. Other renewable sources such as hydro have adverse effects on the aquatic life and sometimes real threat to damaging the biodiversity spot of many endangered species [13]. Also, other closely related issues are the risk of the flash flood in case of hydropower, noise pollution in case of wind power, water contamination, soil erosion, and deforestation during site development for the installation and construction phase of microgrid projects.

- 4) **Institutional:** Institutional organization of the energy sector in the majority of developing economies is government owned which has all the authority and responsibility for generation, transmission, and distribution with scaled-down trust between state and central federal government structure divided into several bodies. Majority of times disarray and insufficient coordination including a lack of authority which certainly creates an unstable economic environment which significantly increases the risk and sometimes reduces the investments thus causing significant obstacles in the deployment of microgrid projects. Lack of dedicated institution, policies, and planning guidelines related to renewables. The absence of clearly defined roles, complicated and inconsistent licensing procedure. Difficulty in obtaining prime land with complicated, slow, lengthy and opaque project clearances process.
- 5) **Technical:** Technical issues include inadequate technology and lack of necessary infrastructure to support the deployment of microgrids. Inability to integrate the renewable energy technologies into the existing power system and lack of proper physical facilities for local transmission and distribution networks, equipment's and services are few of significant barriers to the development of microgrid projects in developing countries. Controlled grid connection is another apprehension, predominantly for distributed technologies and in cases of a vertically integrated power sector. Lack of skilled local human capital force for operating and maintaining the energy projects are additional issues being encountered in developing nations

## 2. Passive and Active distribution

Electrical power network is in the era of power transition from passive stable distribution network of unidirectional power flow to an active distribution network of bidirectional power flow. An electrical system without RES units is passive as power is supplied from the utility grid and customers are connected with unidirectional power flow from generation to the load. The distribution network becomes active once RES units are added in the current distribution network which leads to bidirectional power flow in the system. To support this transition in the distribution network, more emphasis should be given for the development of sustainable electrical distribution network in the developing nations while developed nations should address the technical and economic challenges associated with this transition. It requires to integrate flexible, supervisory and intelligent control incorporating a smart system. To harvest clean renewable energy, active distribution network employ future technologies to progress towards smart-grid/microgrid. Several countries departments of science and technologies and technical reports from institutes indicate that development of active intelligent distribution network has gained momentum. The factors which are in favour of advancement of such distribution networks are (i) customer demand of highly reliable power supply distribution (ii)

nations commitment for carbon emission reduction by 50% till 2050 (iii) policies design to accommodate RESs (iv) better network asset utilization and management by network operators with replacement of inefficient old equipment's, etc.

Microgrid requires superior network management and control to achieve the stable, secure, optimal operation and mode switchover without violating grid regulation and system constraint. Active network management of microgrid needs Central Control & Management System (CCMS), Renewable Energy Controller (REC), Energy Management System (EMS), Protection & Coordination System (PCS). REC look after the local control functions of RES for optimal power generation. PCS corresponds to microgrid faults and main grid faults to ensure the correct protection of microgrid with adaption to change in the fault current due to change in the microgrid operation mode from grid-connected to standalone mode. CCMS performs the overall operation and control functions of the microgrid. The primary role of CCMS is to maintain reliability by power-frequency control, power quality, voltage regulation by reactive power control, economic load dispatch, generation scheduling, and grid power (buy/sell) management. All the controllers are designed to operate in an autonomous mode with an option for manual interventions at any time required. Application of discussed controllers will provide active distribution network dispatch with microgrid for secure and economical operation in the grid-connected or standalone mode of operation. Several issues need extensive research in the area of microgrid management system design in a real sense to make it intelligent for active distribution network development.

### **3. DC, AC and hybrid microgrid system**

This section discusses the various advantages of microgrid based on the type of its supply to the load.

#### **3.1 DC microgrid system**

As shown in Fig. 1(a), the PV, wind, other renewable sources, battery, and the load is connected to DC bus with appropriate individual converter system. The DC bus is connected with the utility grid with bi-direction DC-AC converter for power exchange for maintaining the power balance. The advantage of DC microgrid are as follows:

- 1) Higher energy efficiency and reduced energy conversion losses with the reduction in the used on converters.
- 2) Easier RES integration, control, and coordination as control solely based on DC voltage.
- 3) More efficient supply to the load
- 4) RES generation and load fluctuations are easily managed using a battery to supply deficient power.
- 5) Optimal operation of rotating renewable generators with the elimination of the need for synchronization.
- 6) Easier to damp circulating current between RES.
- 7) Grid integration is easier

Most of the load work on AC and requirement of inverters to convert the DC supply to AC is its only disadvantage. Also, in DC microgrid distribution system, the voltage drops in a

subsequent part of the network, and at the far end of the network the voltage level is low, hence requires intermediate voltage boost in case of medium to vast DC microgrid distribution network.

### **3.2 AC microgrid**

The utility grid is connected to the AC microgrid via AC bus, and it controls the connection and disconnection using a circuit breaker depending on the system condition. The Fig. 1(b) shows AC microgrid structure in which PV, wind, other renewable sources, and the battery is connected with the suitable converter to the AC bus and load is directly connected without any power electronics interface. The AC microgrid is more preferable considering the facts that almost all the electrical load works on AC supply system and most dominant in the research and development. The advantage AC microgrid is that it directly connects with the utility grid without any bi-directional converter. The disadvantage is that it requires a sophisticated control system and operation & management is difficult.

### **3.3 Hybrid microgrid**

The hybrid microgrid consists of AC as well as DC bus in microgrid structure as shown in Fig. 1(c). The AC bus directly connects to the utility grid without any converter and supply power to loads. The DC bus connects PV, wind, other renewable sources, and battery directly and can supply power to DC loads if any. The power exchange between AC bus and DC bus occurs using a bi-directional converter to provide power to AC loads, store cheap utility power in batteries and perform various grid support functions like ancillary support, grid voltage support, etc. The hybrid microgrid has advantages of DC as well as AC microgrid which overcomes the disadvantage of both structures.

## **4. Operation and control of microgrids**

### **4.1 Microgrid operation modes**

Microgrid operates in two modes which are grid-connected mode and Islanded mode. The grid-connected mode is divided into two operating modes as power-mismatched operation and power-matched operation as per power exchange between microgrid and utility grid [14]. In the power-mismatched mode of operation active power ( $\Delta P \neq 0$ ) and reactive power ( $\Delta Q \neq 0$ ) are not equal to zero and current flows between microgrid and utility grid. If  $\Delta P > 0$ , the power flows from network to microgrid to cater the load demand as power generation from RES is insufficient and if  $\Delta P < 0$ , the energy flows from microgrid to the network after meeting load demand as power generation from RES is surplus. In the power-matched operation mode, active ( $\Delta P = 0$ ) and reactive ( $\Delta Q = 0$ ) is balanced which means that generated power from RES meets the load demand and no power exchange between microgrid and grid occurs. Hence this mode is most economical microgrid operation mode. Similarly, reactive power is excessive if  $\Delta Q < 0$  and deficient if  $\Delta Q > 0$ , this variation in reactive power is categorized under power mismatch.



#### *4.1.1 Grid connected mode of operation*

In this mode of operation, the microgrid is connected with utility at Point of Common Coupling (PCC) to exchange power with the distribution network. The microgrid can transfer its mode using connection/disconnection controls as:

- 1 When microgrid is operational and connected with utility via PCC, it can be disconnected from utility by grid disconnection control; when not connected with utility, it can be connected by grid connection control.
- 2 In grid disconnection control, microgrid stop working in grid-connected mode and switch to Islanded mode while in grid connection control, microgrid stop working in Islanded mode and switch to the grid-connected mode of operation.
- 3 When microgrid is operating in grid-connected or Islanded mode, it can stop working using shut control.

#### *4.1.2 Islanded mode of operation*

In this mode of operation, the microgrid is disconnected from the utility due to grid-faults or scheduled disconnection operation. The RESs, Battery Storage System (BSS), other renewable sources and load work independently with individual control functions [15]. The electricity generated in this mode might not be sufficient all the time to cater to the load demand, and hence, it is necessary to prioritize the critical loads. In an Islanded mode of operation is carried by shedding unimportant load during inadequate availability of electrical energy in microgrid using load-shedding control to ensure the uninterrupted electricity supply [16].

### **4.2 Microgrid control modes**

Microgrid works mostly in three commonly used control modes: master-slave combined control mode and peer-to-peer. The selection of microgrid control mode depends on its size and capacity for example small microgrid mostly work in master-slave control mode [17]. Apart from these overall control modes, inverter controls are also used which are namely: active-reactive (P-Q) power control, Voltage-frequency (V-f) control, droop control, etc. some of these microgrid controls are discussed in following sections to understand its functions [18].

#### *4.2.1 Master-slave control mode*

In this control mode, the different RESs are controlled with varying tasks of control and methods. One or group of RES act as a master and other RESs are act as a slave. In an Islanded mode of operation, the master RES works in V-f control mode and act as a reference for other slaves RESs similar to a slack bus. In grid-connected operation mode, all RESs work in P-Q control mode and PCC is act as a reference for power flow. The master RES regulates voltage and frequency subjected to load fluctuations, and hence, power generation should be controllable with fast control response. Master control mode has some disadvantages as:

- 1 Master RES working in V-f control has its output voltage constant. The only way to increase the generated power output is to control its current production. Also, to respond to the instantaneous load fluctuations, master RES should have enough adjustable generation capacity analogs to spinning reserve capacity of conventional generators.

- 2 The master RES governs the coordination and control of all other RESs in microgrid system if it fails the complete system will collapse.
- 3 This control mode needs highly accurate and time-bound islanding detection. Since islanding detection is complemented by time-delay and error, without a sound communication system, it is likely to fail; thus, not performing the functions of control strategies.

To support the fast transfer of control functions the following combination of RESs should be used as a master RES as:

- 1 PV + Wind
- 2 BSS + Other stable and easily controlled renewable sources such as fuel cell or micro-turbines, etc.
- 3 PV + BSS or PV + BSS + fuel cell.

The third combination of RESs is more advantageous than first two as it can efficiently use the BSS for quick charge and discharge functions and ability of RES to work in Islanded operation mode of a microgrid for an extended duration. The BSS can provide power support immediately when microgrid switches from grid-connected mode to Islanded mode of operation; hence, effectively damp the significant voltage and frequency fluctuations. With increasing research in this area and use of other renewable generators to efficiently support the microgrid operation, the several other combinations are available on scientific literature [7-11].

#### *4.2.2 peer-to-peer control mode*

This control mode strategy is based on the idea of ‘plug-and-play’ which is mostly used on power electronic technologies. In this control mode, all RESs are equal and no master-slave RES combination in the microgrid system. Each RES participates in active and reactive power regulation with pre-set of control functions to maintain the voltage and frequency stability in microgrid [2]. Each RES uses droop control in this control mode of the microgrid. In peer-to-peer control mode, all RESs under droop control work to regulate voltage and frequency in Islanded mode of microgrid operation. When load fluctuations occur, the changes in the voltage and frequency automatically distributed between RESs based on droop factor. RESs adjust its output frequency and voltage amplitude to achieve a new steady state of microgrid with appropriate distribution of output power generation. The droop control permits automatic load fluctuation distribution between RESs thus the voltage and frequency of microgrid also changes accordingly; hence, this control mode is essentially a proportional control. The droop control functions of RESs remains unchanged in both grid-connected and Islanded mode of microgrid operation and enable a smooth transition between two modes. In grid-connected mode, the droop control permits RESs independent control based on voltage and frequency at PCC which makes voltage and frequency regulation easily achievable. This does not require the need of communication system for RES which helps in the flexible and smooth deployment of the microgrid. This control mode is simple, flexible, reliable and easily deployable with little compromise of microgrid stability in terms of voltage and frequency.

#### *4.2.3 combined control mode*

As the name suggests, the combined control mode is a combination of advantages peer-to-peer control mode and master-slave overcoming disadvantages of both modes. The microgrid may have multiple RESs or group of RESs (for example PV farm, wind farm, etc.,) with the

randomness of power generation profile or easily controllable other renewable sources. Control functions of RESs vary for different types of RESs, and the single control mode is not sufficient to meet the operational requirements of microgrid [3]. Considering dispersive aspects of RESs and loads in the microgrid needs different types of control modes. Hence, both the control modes can work in combination to achieve the stable, reliable and smooth operation of the microgrid.

### 4.3 Inverter control modes

RES integrated with the converter in the microgrid to operate either in parallel with utility in grid-connected mode or independently in Islanded mode. In the grid-connected mode of operation, RES requires to control the generated active and reactive output power to maintain the load-demand balance in the microgrid. The overall electricity generation capacity of the microgrid is small as compared to utility, and it regulates the rated voltage and frequency of in microgrid; hence the converters (specifically inverters) works in P-Q control [19]. In an Islanded mode of microgrid operation, one RES or group of RESs considered as a reference/slack bus to maintain the rated voltage and frequency and work in V-f control mode or droop control mode. These methods will be discussed in the following sections to understand the control concept.

#### 4.3.1 P-Q control

In this mode of control, the basic control function of the inverter is to control the generated active and reactive power of RES. RES inverter generates an active and reactive power based on pre-set power reference based on the power control algorithm. RES with small generation capability can be integrated into the utility on constant power generation control, and grid manages the voltage and frequency regulation [2]. In such a scenario, RES only supplies or absorbs power and do not contribute to the regulation of voltage and frequency. Grid voltage oriented decoupled control algorithm is the basis of P-Q control, in it inner-loop looks after the output current control and the outer-loop adopts output power control. The mathematical model of P-Q control of inverter output voltage in  $dq$  reference is given as:

$$v_d = Ri_d + L \frac{di_d}{dt} - \omega Li_q + u_d \quad (1)$$

$$v_q = Ri_q + L \frac{di_q}{dt} - \omega Li_d + u_q \quad (2)$$

Where  $u_d$  and  $u_q$  are inverter terminal voltage,  $\omega Li_d$  and  $\omega Li_q$  are cross-coupling terms which get eliminated in feedforward compensation by subsequent control. The Proportional Integral (PI) control is used in the outer power control loop which is expressed as:

$$i_{dref} = (P_{ref} - P) \left\{ k_p + \frac{k_i}{s} \right\} \quad (3)$$

$$i_{qref} = (Q_{ref} - Q) \left\{ k_p + \frac{k_i}{s} \right\} \quad (4)$$

Where  $P_{ref}$  and  $Q_{ref}$  are active and reactive power reference,  $i_{dref}$  and  $i_{qref}$  is  $d$ -axis and  $q$ -axis current reference,  $k_p$  and  $k_i$  is proportional and integral gains, respectively. When grid voltage



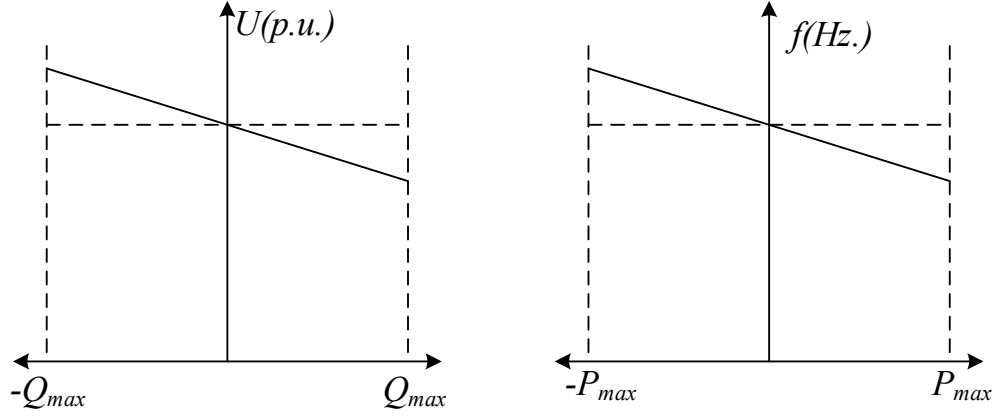


Fig. 4. Microgrid droop control characteristics

#### 4.3.2 V-f control

In V-f control, the output of inverter voltage and frequency is constant to enable RES operation in slave mode and critical loads when the microgrid is disconnected from the utility. It is necessary to curtail load in Islanded mode of operation considering the low generation capacity of the microgrid to maintain the continuity of power supply to critical loads. Hence, this control must be able to respond and detect load switching. To maintain the constant output, based on feedback from the inverter the AC side voltage is regulated and the dual-control scheme is adopted with voltage control in outer-loop and current control in inner-loop [20]. The function of voltage control in outer-loop is to maintain output voltage constant and current control in inner-loop to accelerate the fast response against load fluctuations or disturbances. In V-f control mechanism, the current control in the inner loop has wide bandwidth in the inverter control which increases the speed of dynamic response of inverter dynamic response ability and adaptability for non-linear load disturbances with reduced harmonic distortion in output voltage. This control has a high dynamic response and steady-state accuracy because it makes the best usage of system status information. In terms of decoupling and control functions, the V-f control is similar to P-Q control. Fig. 3 show the microgrid V-f control schematic, the reference voltages  $U_{1dd}^*$  &  $U_{1dq}^*$  and measured voltages  $U_{1dd}$  &  $U_{1dq}$  adopted in this for voltage control outer-loop and current control inner-loop are specified [21].

#### 4.3.3 Droop control

The droop control method is based on power converters parallel-connection technology. This control algorithm is implemented by mimicking the droop characteristics of traditional generational connected to the utility. The voltage and frequency output of Voltage Source Inverter (VSI) or Voltage Source Converter (VSC) is controlled according to variation of the power output. The microgrid operating in Islanded mode with multiple RES inverters connected in parallel, individual inverters active and reactive power equation is expressed as:

$$P_n = \frac{VV_n}{X_n} \delta_n \quad Q_n = \frac{VV_n - V^2}{X_n} \quad (7)$$

Where  $V$  is the voltage at inverter point of connection,  $V_n$  is the output voltage of the inverter,  $\delta_n$  is an angle between  $V$  and  $V_n$  and  $X_n$  is output impedance (reactance) inverter. From equation (7) it is evident that active inverter power mainly depends on the angular difference ( $\delta_n$ ) between the voltage at the point of connection (or PCC) and inverter output voltage while

reactive power mainly on voltage magnitude. By controlling the output frequency, the inverter phase can be controlled, and the voltage can be directly controlled with appropriate triggering strategy. The frequency of the inverter is given as:

$$f_n = \frac{\omega_n}{2\pi} = \frac{d\delta_n}{dt} \quad (8)$$

From equation (7) & (8) it is evident that inverter output voltage regulates its reactive power output and frequency regulates its active power. The inverse droop control strategy is to control its active and reactive power outputs based on measured grid voltage magnitude and frequency by calculating the predefined droop control characteristics [2]. The inverter output voltage is regulated by measured active power; hence this control mode is inverse droop control. Fig. 4 show the microgrid droop control characteristics for active and reactive power.

The RES inverters can use any of these discussed control methods, and output can be controlled using local measurement data to achieve smooth and reliable operation of the microgrid. The control methods discussed in this chapter is elementary in understanding to make the basis of operation and control concept of the microgrid.

#### **4.4 operation and management**

A microgrid is operated and managed using various controllers such as RES, CCMS, EMS, and PCS which work to coordinate and manage several important functions for smooth and reliable operation. The detail functions of these controllers are discussed as follows:

##### *4.4.1 Renewable Energy Controller*

REC main function is to autonomously control the flow of power and voltage profile of load response to contingency and load transitions. Here ‘autonomously’ suggests without any communications or control command from the CCMS. REC also participates in generation scheduling, load management, and demand-side management by controlling the BSS or other storage devices. Also, REC must ensure that each RES quickly picks up its generation to provide power to its load in Islanded mode and automatically reconnect to the grid to work in coordination with CCMS. The most important aspect of REC is its fast response for the locally measured voltages and currents regardless of the information from the other RECs. This functionality enables RES to work as plug-and-play devices which also helps of new RES at any point in the microgrid without compromising the protection and control of newly added RES generation. Another important function of REC is that it does not communicate other RECs in the microgrid independently and it never supersede the CCMS control commands.

##### *4.4.2 Central Control and Management System*

CCMS is the main controller in the microgrid and regarded as the brain of a microgrid. CCMS executes all commands for operation, management, and control of microgrid through RECs and other controllers. The main functions of CCMS are (i) it maintains the rated voltage and frequency at all load points through power-frequency and voltage controls (ii) it maintains the power balance in the microgrid (iii) optimized energy generation and load dispatch (iv) load management through load shedding (v) monitoring and data storage (vi) supervisory controls. CCMS mostly designed to work autonomously but it can be switched to manual control whenever it's required. It also manages the functions of EMS and settings of PCS depending on system configuration changes. Some important function of CCMS in grid-connected mode are (a) system monitoring and diagnostic by collecting information from RESs (b) state estimation of overall microgrid and RESs (c) security assessment (d) monitoring of economic

RESs generation scheduling (e) monitoring and controlling of active and reactive generation from RESs (f) ensuring the grid synchronization to enable power exchange. Important functions of CCMS in Islanded mode are (a) maintaining voltage and frequency by initializing optimized active and reactive power control from RES generators (b) initializing efficient and optimum load shedding or load curtailment algorithms (c) management of BSS for optimum utilization and maintaining power balance within limit (d) executing connection and disconnection with utility.

#### *4.4.3 Energy Management System*

EMS provides the reference of active power, reactive power, voltage and frequency for REC of each RES. To achieve the function of calculation of various reference parameters, EMS uses state-of-art communication system protocols and embedded algorithms based on Fuzzy, artificial intelligence or other novel computational mathematical morphology [20]. The setpoint is calculated based on operation, management and control requirements of the microgrid. The important functions of EMS are (a) RES able to meet the load demand with customer satisfaction (b) microgrid able to meet the operational guideline set by grid satisfactorily (c) optimization of RES generation to meet guidelines of green-house-gas and CO<sub>2</sub> emission reduction (d) optimization of renewable energy fraction of generation (e) maintaining the higher efficiency of RES generation.

#### *4.4.4 Protection and Coordination System*

PCS main function in a microgrid is to ensure protection against faults within the microgrid and main grid operating in grid-connected and Islanded mode. The protection scheme should be adaptive and under the control of CCMS to change the relay settings as per the scenarios in the microgrid. Relays threshold detection and coordination settings should correspond to change in the fault current level. To achieve this, the strong backbone of a communication system is needed which facilitate communication between CCMS, PCS, and REC. When a fault is detected in the utility side, PCS straightway issues the command to PCC circuit-breaker to disconnect and switches microgrid operation to Islanded mode to maintain the supply the critical loads. For utility faults, PCS allows fault-ride-through following the grid code in the grid-connected mode for a stipulated time in case of temporary fault conditions before issuing a command for the disconnection. For faults within the microgrid, the PCS disconnects the faulted section of the microgrid to keep good part stable and smooth operation. Under-frequency and undervoltage relays are used concerning bus voltage for RES protection in case of severe faults in the microgrid. PCS also governs the resynchronization of microgrid with utility and initiates the switchover from Islanded to the grid-connected mode by issuing circuit breaker commands. More details of protection schemes and coordination algorithms will be discussed in the book chapter in details in various chapters. The protection philosophy is different for microgrid in comparison to conventional power transmission or distribution system due to (a) bidirectional power flows between generators and loads in the radial microgrid system (b) microgrid distribution system is active because of RES and (c) the short-circuit level of microgrid is not constant, and it changes significantly depending on mode or operation as well as a number of RESs active in the system.

## **5. Monitoring and protection of microgrid**

### **5.1 Monitoring of microgrid**

The success of microgrid operation, control, and management functioning as an active distribution network depends on the cost-effective and efficient communication system. The Supervisory Control And Data Acquisition (SCADA) is most preferable along with Distribution Network Operator (DNO) to achieve these function in the microgrid system. The increased penetration of RES generation the network connection becoming more complex day-by-day due to constraints of thermal limit, voltage limit, wired connection complications, etc. These constraints are creating unwanted hurdles in the future incorporation of RES generation which demands the active distribution network system and cost-effective solutions to overcome these challenges. In a conventional distribution system, SCADA is mainly available voltage level 6.6 kV-11 kV and higher voltages network with high-bandwidth local area and wide area networks (LAN and WAN). SCADA function varies from several tasks such as data acquisition, remote switching, alarm indication, data processing, emergency control, demand-side management, human-machine interface (HMI), etc. SCADA system is very secure and robust in terms of security and functioning. SCADA uses a combination of communication circuits such as pilot cables, standard copper cable, optical fiber, mobile telecommunication, radio. The optical fiber-based communication circuit is the fastest and most reliable in comparison of others, but in rural areas, the copper cable-based communication circuit is used due to cost constraints. DNOs is similar to System Operators (SOs) in the power system, and it operates in urban as well as rural networks. DNOs uses several remote terminal units for a variety of functions such as switch change time tagging and alarms with 1 ms accuracy, relay connections, programmable logic sequence and digital outputs with pulse duration. Therefore, the active distribution network management control centers should be located at strategic substations instead of remote location which host DNOs with the SCADA system. Microgrid system has typically two types of SCADA systems as a centralized and decentralized system.

#### *5.1.1 Centralized system*

The SCADA has some important functions which need to be controlled centrally, e.g., load scheduling, load switching, load management and implementation of load curtailment. However, the main challenge is the appropriate communication infrastructure for reliable data information and control command transmission. High voltage substations have real-time units installed, but microgrid connects to low voltage substations which might not have installed real-time units and appropriate communication system. It will lead to slow switch status detection which in turn slow the SCADA system to operate its functions. Centralized system with information of network diagram, switch operation and sequencing details, historical components database, hardware maintenance schedule, skilled and experienced personnel, switch control sequence, etc., will be helpful to implement intelligent switch control algorithm for microgrid operation and smooth control. Moreover, the centralized system needs costly communication system to provide efficient operations if it lacks that it will have slow SCADA response which might lead to the risk of single point system failure.



### *5.1.2 Decentralized system*

The decentralized system has widespread small SCADA system installed at various substations located in urban and remote areas. It is more advantageous for single DNOs to control the number of small SCADA system which can provide efficient management and control. The dispersed SCADA system requires dedicated support and communication workstations. The decentralized system has the advantage of low-cost communication system, better switch change response, cost-effective logic controllers, etc. However, it might suffer from high upfront investment cost, suitable maintenance facility, field visit and complexity in the integration of dispersed SCADAs with a central SCADA system. With the advancement in technology, the implementation and operation of such a system may become cost-effective and feasible in a few years. The aim of this section to introduce DNO and SCADA system with the type of control architecture, there are numerous components, functions, and modules which plays a significant role in monitoring. However, more detail description and its functioning can be found in scientific literature as well as in textbooks and not elaborated in this chapter.

## **5.2 Protection of microgrid**

Microgrid operating under normal condition should work in grid-connected mode and the case of any fault or disturbance it must dis-connect from utility and work in Islanded mode. Microgrid with RESs, BSS and other renewable sources is capable of catering load demand and if not it may initiate optimize load shedding control algorithm to supply critical loads. The main function of the protection system in the microgrid to provide stable and smooth operation of a microgrid during a contingency. The protection system determines under what conditions microgrid should be disconnected from the utility, which section of microgrid under faulted condition should be isolated and how to provide coordinated protection. The elements of the protection system feature and performance of microgrid is not similar to the distribution system due to inverter-based RES the operating characteristics are not the same due to (a) inverter operating characteristics are not consistent (b) different RES inverter has its unique design and not uniform (c) RES inverter design depends on system requirement and operational conditions. The protection system of microgrid design is very complex and require prior research to understand the dynamics of microgrid operation for grid-connected and Islanded mode. This section will put forward basic microgrid protection concept and issues.

### *5.2.1 Microgrid protection functions*

Microgrid protection system has to work in both grid-connected and Islanded mode. In grid-connected mode, the multiple RES, BSS, and other renewable energy sources influence the fault current, other electrical parameters significantly; hence, traditional protection schemes fail to detect and locate the faults. In Islanded mode, the inverter protection functions may force to disconnect the RES and inverter operation of forced RES disconnection need to be blocked by the protection system. Before the introduction of the microgrid in the mainstream, the RESs integrating with the utility was not working independently, and utility protection system was under tremendous stress to maintain the operation of RES. The accurate and reliable protection scheme is a key aspect for microgrid control and operation which is highly complicated in implementation. Based on current scientific literature and research, microgrid protection is the main area of research and development technology. The microgrid protection schemes mainly

perform functions as (a) Fast RES disconnection from utility network in the event of a fault on the utility side (following the newly introduced fault-ride-through grid conditions) does not affect the utility distribution network protection. The generation capacity of a microgrid is not significant as compared to the capacity of utility and disconnection of RES will not affect the power imbalance significantly. (b) Prevention of unwanted disconnection of microgrid from the utility which will create momentary power instability in utility and may trigger other protection systems to bring network in stable operating condition. (c) Disconnection operation from the utility in normal operating condition for scheduled maintenance. (d) Re-connected or resynchronization of microgrid with the utility for enabling power exchange. (e) RES protection and coordination with other protection systems.

### *5.2.2 Microgrid protection schemes*

#### *Differential protection*

The issues in the protection of microgrid due to the integration with the utility is mitigated using Differential Protection Scheme which is installed at PCC. DPS acts as primary protection and is installed at PCC to protect microgrid from utility-side disturbances in grid-connected mode and severe faults in Islanded mode. DPS works on Kirchhoff node current law and its best scheme for the protection of microgrid utility installed at PCC. The DPS pickup setting and percentage differential setting forms AND gate to detect and isolate fault conditions. DPS is highly sensitive, accurate and simple to implement for the protection of microgrid having multiple RES. Research and development in this area also persisted, and DPS with advanced computational methods and in combination with machine-learning has been reported in several scientific works of literature with better accuracy and detection sensitivity. DPS is highly reliable and dependable protection scheme, and the only disadvantage is the high cost. In the following chapters, the other protection schemes will be discussed in detail.

#### *Backup protection*

DPS circuit breaker failure is not common but to protect it, neighboring circuit breaker operates to isolate the fault if it fails to perform. Backup protection is provided using overcurrent relay (OCR) with specific time-delay setting. In the event of DPS failure due to certain circumstances and central DPS goes offline, OCR performs primary protection to prevent complete protection system loss from service. OCR also serves as backup protection for internal faults of the transformer and internal microgrid faults to avoid excess current flow from RES. The utility-side protection scheme such as distance protection serves as backup protection of PCC with time delay setting. With the application of wide area monitoring system penetration in distribution and microgrid for advanced control and management, the advanced backup protection schemes based on negative sequence, rate of change of impedance and other important system parameters are reported and available in the scientific literature. New Islanding schemes based on advanced measurement technology with highly fast and accurate detection of stable and unstable microgrid operating conditions are reported in the scientific research and will be discussed in following chapters.

## *Directional protection*

The other very important protection scheme for the microgrid is Directional Current Protection (DCS). The microgrid is considered as an active distribution network, and power flows in bi-direction due to multiple RES installed. DCS which plays a very important role in the detection of reverse power flow and helps to maintain the stable microgrid operation. During severe faults within the microgrids network, depending on the fault location and sections, the current contributed from other sources may increase the fault current level and damage the pieces of equipment. DCS helps to divide the microgrid network into small-small parts by detecting reverse power flow and help to prevent harm to the costly equipment's. Directional Impedance Relay (DIR) acts as a primary protection scheme in the microgrid distribution system to locate and isolate the fault. DCS and DIR work in coordination to detect, isolate the faulted section and protect the RES generators from excessive current flow damage. In the event of a fault at PCC and failure of the PCC protection system, DCS can also provide backup protection and initiate the microgrid disconnection with specific time-delay settings.

## **6. References**

- [1] Bansal, R. ed., 2017. Handbook of distributed generation: electric power technologies, economics and environmental impacts. Springer.
- [2] Li, F., Li, R. and Zhou, F., 2015. Microgrid technology and engineering application, chapter 2, pp 11-27. Elsevier.
- [3] Chowdhury, S., Chowdhury, S.P. and Crossley, P., 2009. Microgrids and Active Distribution Networks, chapter 1, pp.1-12. IET Renewable Series 6.
- [4] Kumar, A., Singh, A.R., Deng, Y., He, X., Kumar, P. and Bansal, R.C., 2019. Integrated assessment of a sustainable microgrid for a remote village in hilly region. Energy Conversion and Management, 180, pp.442-472.
- [5] Kumar, A., Singh, A.R., Deng, Y., He, X., Kumar, P. and Bansal, R.C., 2018. Multiyear load growth based techno-financial evaluation of a microgrid for an academic institution. IEEE Access, 6, pp.37533-37555.
- [6] Kumar, A., Singh, A.R., Deng, Y., He, X., Kumar, P. and Bansal, R.C., 2018. A novel methodological framework for the design of sustainable rural microgrid for developing nations. IEEE Access, 6, pp.24925-24951.
- [7] Kumar, A., Sah, B., Singh, A.R., Deng, Y., He, X., Kumar, P. and Bansal, R.C., 2017. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. Renewable and Sustainable Energy Reviews, 69, pp.596-609.
- [8] Singh, R. and Bansal, R.C., 2018. Review of HRESs based on storage options, system architecture and optimisation criteria and methodologies. IET Renewable Power Generation, 12(7), pp.747-760.
- [9] Singh, R. and Bansal, R.C., 2019. Optimization of an autonomous hybrid renewable energy system using reformed electric system cascade analysis. IEEE Transactions on Industrial Informatics, 15(1), pp.399-409.
- [10] Singh, R., Bansal, R.C., Singh, A.R. and Naidoo, R., 2018. Multi-objective optimization of hybrid renewable energy system using reformed electric system cascade analysis for Islanding and grid connected modes of operation. IEEE Access, 6, pp.47332-47354.

- [11] Singh, R., Bansal, R.C. and Singh, A.R., 2018. Optimization of an isolated photo-voltaic generating unit with battery energy storage system using electric system cascade analysis. *Electric Power Systems Research*, 164, pp.188-200.
- [12] Al Mamun K, Amanullah MTO. *Smart energy grid design for island countries*. Springer 2018.
- [13] Merritt, N.R., Chakraborty, C. and Bajpai, P., 2015, July. A control strategy for islanded operation of a Voltage Source Converter (VSC) based distributed resource unit under unbalanced conditions. In *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)* (pp. 1550-1555). IEEE.
- [14] Saha, S., Roy, T.K., Mahmud, M.A., Haque, M.E. and Islam, S.N., 2018. Sensor fault and cyber attack resilient operation of DC microgrids. *International Journal of Electrical Power & Energy Systems*, 99, pp.540-554.
- [15] Gaztanaga, H., Etxeberria-Otadui, I., Bacha, S. and Roye, D., 2006, November. Real-time analysis of the control structure and management functions of a hybrid microgrid system. In *IECON 2006-32nd Annual Conference on IEEE Industrial Electronics* (pp. 5137-5142). IEEE.
- [16] Yongbiao, Y., Weiliang, L., Jie, S., Kun, H., Lu, C. and Li, H., 2012, September. The wide-area measurement technology application in micro grid. In *2012 China International Conference on Electricity Distribution* (pp. 1-5). IEEE.
- [17] Kaletsanos, A., Xepapas, F., Xepapas, S. and Manias, S.N., 2003, June. Nonlinear control technique for three-phase boost AC/DC power converter. In *IEEE 34th Annual Conference on Power Electronics Specialist, 2003. PESC'03.* (Vol. 3, pp. 1080-1085). IEEE.
- [18] Sarkar, T., Dan, A.K., Ghosh, S., Das Bhattacharya, K. and Saha, H., 2018. Interfacing solar PV power plant with rural distribution grid: challenges and possible solutions. *International Journal of Sustainable Energy*, 37(10), pp.999-1018.
- [19] Patrao, I., Figueres, E., Garcerá, G. and González-Medina, R., 2015. Microgrid architectures for low voltage distributed generation. *Renewable and Sustainable Energy Reviews*, 43, pp.415-424.
- [20] Guo, Z., Li, S. and Zheng, Y., 2020. Feedback linearization based distributed model predictive control for secondary control of islanded microgrid. *Asian Journal of Control*.
- [21] Ambia, M., Al-Durra, A., Caruana, C. and Muyeen, S.M., 2012. Islanding operation of hybrid micro-grid system with power management control scheme. In *Proceedings of the IASTED International Conference on Power and Energy Systems, EuroPES 2012* (pp. 26-33).