REVIEW OF THE AC/DC MICROGRID OPERATION AND CONTROL

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DER	Distributed Energy Resource
DG	Distributed Generation
DES	Distributed Energy Storage
T & D	Transmission and Distribution
UC	Unit Commitment
CHP	Combined Heat and Power
PCC	Point of Common Coupling
DMS	Distributed Management System
SS	Static Switch
ESC	Energy Capacitor System
MGCC	Microgrid Central Controller
MC	Microsource Controller
LC	Load Controller
EMS	Energy Management System
OPF	Optimal Power Flow
MILP	Mixed Integer Linear Programming
ESS	Energy Storage System
PSO	Particle Swarm Optimization
TOU	Time Of-Use
RTP	Real-Time Pricing
CPP	Critical Peak Pricing
SDP	Semi-Definite Programming
MV	Medium Voltage
MS	Management System
SMO	Single Master Operation
MMO	Multi Master Operation
LV	Low Voltage
PI	Principle Investigator
SOC	State Of Charge

SST	Solid State Transformer
IED	Intelligent Electronic Device
CB	Circuit Breaker
MCCB	Molded-Case Circuit Breaker
VR	Virtual Resistances
DBS	Distributed Bus Signaling
PLS	Power Line Signaling
CC	Central Controller
LC	Local Controller
PI	Proportional Integral
PD	Proportional Derivative
PLC	Power Line Communication
POE	Power Over Ethernet
USB	Universal Serial Bus
POH	Power Over HD
EV	Electric Vehicle
PV	Photovoltaic
SCADA	Supervisory Control And Data Acquisition
HF	High Frequency
MF	Medium Frequency
RES	Renewable Energy Sources
MPPT	Maximum Power Point Tracking
MMC	Microgrid Master Controller
MAS	Multi-Agent System
VSI	Voltage Source Inverter

ABSTRACT

As defined by the U.S department of energy, a microgrid is a group of inter-connected loads and distributed energy resources (DERs) with the ability of self-supply and islanding. The significant advantages of microgrids have resulted in extensive research and development efforts and rapidly growing implementation in electric power systems. There are, however, still many challenges to be addressed in order to efficiently design, control, and operate microgrids when connected to the grid, and also when in islanded mode.

Based on the type of voltages and currents in the network, different microgrid types can be considered, including AC microgrids, DC microgrids, and Hybrid AC/DC microgrids. This thesis presents a review of AC, DC and Hybrid microgrids with a focus on control, operation, and planning issues. A thorough comparison between these microgrid types is further provided based on the system layout and the type of DERs that are commonly utilized. Communication issues are also investigated to demonstrate and compare the existing deployment practices. The thesis is concluded by providing a list of potential areas of research associated with AC, DC, and hybrid microgrids.

CHAPTER 1

INTRODUCTION

A Microgrid is a small-scale version of the centralized power system that generates, distributes, and adjusts the flow of electricity from local distributed energy resources (DERs) to local loads. DERs consist of distributed generation (DG) and distributed energy storage (DES) installed at utility facilities, e.g., distribution substations, DG sites, or consumer locations. A microgrid must have three different characteristics: 1) the electrical boundaries must be clearly defined, 2) there must be a control system in place to dispatch DERs in a coordinated fashion and maintain voltage and frequency within acceptable limits, and 3) the aggregated installed capacity of DERs and controllable loads must be adequate to reliably supply the critical demand during islanded operation [1]. The Microgrids may be operated in two modes:

1) Interconnected to the grid: under this mode, the microgrid can import, export, or have zero power exchange with the grid. This type of operation is generally designed for normal conditions (no system contingencies), and its objective is to improve grid performance and efficiency by using local DERs, e.g., to defer capacity investments, reduce system losses, and improve local reliability [1].
2) Disconnected from the grid: under this mode, the microgrid is allowed to operate islanded from the grid; this is also commonly known as intentional islanding. This type of operation requires the DERs within the microgrid to be dispatched in a coordinated fashion to provide voltage and frequency regulation. Successful islanded operation may also entail the implementation of energy demand management, e.g., demand response or curtailment, to achieve generation-load

balance. This type of operation is generally intended to provide service to remote locations (permanent islanded operation) or to provide continuous supply during contingencies (temporary islanded operation). In the latter case, the microgrid is expected to return to interconnected operation once the contingency has been addressed [1].

The very first modern microgrids were organized in university campuses, believably due to the availability of funding for research initiatives and internal expertise in engineering and science. Commercial and industrial consumers found that microgrid deployment is becoming an increasingly attractive solution that require premium reliability and power quality levels and/or are interested in following economic benefits from the strategic dispatch of their DERs, e.g., consumers who want to take advantage of available incentives and use idle capacity from backup generation to export power to the grid.

More recently, community microgrids have appeared as viable alternatives to address the rising common demands for electric organizations that are able to provide premium reliability and power quality levels while being inexpensive and ecologically friendly. Community microgrids aim primarily at supplying electricity to a group of consumers in a neighborhood or several connected neighborhoods in close proximity (Figure 1.1). Benefits of Community Microgrids are:

1. Security: Maybe the most outstanding benefit of community microgrids is the improved security as they could possibly relieve the impacts of physical and cyber threats. Security of power delivery to critical facilities, such as hospitals, emergency response centers, water stations, transportation systems, food banks,

and shelters within the electrical boundaries will be increased by the community microgrids.

2. Resiliency: Resiliency improvement is considered as a complementary value proposition of microgrids. Resiliency mentions to the capability of power systems to withstand low-probability, high-impact events by minimizing possible power outages and quickly returning to normal operating state. These events typically include extreme weather events and natural disasters such as hurricanes, tornados, earthquakes, snowstorms, floods, and cyber- and physical security attacks, and terrorism [1].
3. Reliability: One of the most important benefits of community microgrids is to improve consumers' supply reliability. Electric utilities constantly monitor consumers' reliability levels and perform required system upgrades to improve supply availability and to reach or maintain desired performance. Consumer reliability is typically evaluated in terms of system/customer average interruption frequency/duration indices [1].
4. Emission Reduction: Community microgrids could be attached as rapid enablers of renewable energy integration to distribution networks. Renewable energy resources may cause significant technical challenges when integrated to a distribution network as they produce a variable amount of energy. Community microgrids use the coordinated control of a combination of dispatchable DGs, DES, and controllable loads to "smooth down" the intermittent output of renewable energy resources.

5. Reduced Costs of Recurring System Upgrades: As the demand for electricity increases, today's power system must be amplified by the addition of new generation, transmission, and distribution facilities. Community microgrids deploy DERs to supply local loads, including conventional and renewable DGs and DES, and implement load control to facilitate local grid management. Therefore, while operating in interconnected mode, the additional generating capacity from community microgrids decreases the average and peak T&D system loading, effectively deferring capacity increase or generation investments.
6. Energy Efficiency: Community microgrids could help improve overall energy efficiency by reducing T&D losses and allowing the implementation of optimal load control and resource dispatch. The former is a direct consequence of supplying consumer loads with local generating facilities, and the latter can be accomplished by intelligent control and dispatch of consumer loads.
7. Power Quality: Consumers' needs for higher power quality have significantly increased during the past decade due to the growing application of voltage-sensitive loads, including a large number and variety of electronic loads and light-emitting diodes. Community microgrids provide a quick and efficient answer for addressing power quality needs by enabling local control of the frequency, voltage, and load, and a rapid response from the DES.
8. Lowered Energy Costs: Financial incentives offered to consumers within a community microgrid who would consider load-scheduling strategies according to electricity prices and benefit from locally generated power is a significant driver

in the economic deployment of a microgrid. The reduced energy costs would impact each individual consumer within the community microgrid [1].

Figure 1.1. Community microgrids aim primarily at supplying electricity to a group of consumers in a neighborhood or several connected neighborhoods in close proximity.

1.1 Microgrid Definition

A microgrid comprises various distributed generators, storage systems and controllable loads, which make the microgrid highly flexible and efficient in both power supply and consumption sectors. The main reasons to build a microgrid are to lower the cost of energy supply, improve local reliability, reduce emissions, and enhance power quality [3].

A microgrid has enough generation capacity to supply its load. Therefore, two operating modes, from an operational point of view, are possible for a microgrid: interconnected mode and islanded mode. In the interconnected mode the microgrid is a part of the main grid, and hence it may sell electricity to or buy electricity from the main grid. In this respect, it would be treated as a single controlled load entity within the power system or as a generation resource supporting the main grid. In the islanded mode the microgrid operates independent of the main grid. The required load demand in the microgrid is satisfied using the local generation resources. Therefore, there is no interaction between the main grid and the microgrid in the islanded mode.

The microgrid central controller performs the coordination between the microgrid and the main grid. This coordination is performed by utilizing a day-ahead unit commitment (UC), which optimizes the microgrid operation by scheduling local generation resources. Furthermore using UC, the optimal interaction with the main grid is obtained.

The UC performed by the central controller of a microgrid is considerably different from that of an ISO performed for the main grid. The main differences are [4]-[5]:

- In a microgrid the number of units is limited and may also include renewable energy resources. Large penetration of renewable energy resources, like solar and wind, requires powerful forecasting tools to predict the behavior of these resources accurately and determine the optimal schedule.
- The storage system has a major role in the operation of microgrid due to its considerable size, while this is generally not the case in the main grid. Therefore, the storage system has to be accurately modeled and utilized in a microgrid.
- The impact of the power transmission network in a microgrid is much less than the impact of power transmission network in the main grid. In the

main grid, the power generated at large centralized power plants is transmitted to the large distant loads using high voltage transmission lines. Due to the distance between the producers and consumers, congestion in the transmission lines is probable. Therefore, considering the impact of transmission lines in the main grid UC is necessary. However, in a microgrid the local load is satisfied using the local generation resources (in addition to energy bought from the main grid). Since the loads and generation resources are close to each other, the transmission congestion is less likely, and accordingly the transmission network has reduced impact on UC results.

- The microgrid can buy (or sell) electricity from (or to) the main grid at any time taking its security and economical aspects into account. Therefore, it can simply manage its load and satisfy the load balance by buying or selling electricity. However, this task is not simple for the main grid. Main grids usually trade with the neighbors based on long-term energy trade contracts. So, the main grid is not able to buy or sell electricity whenever it needs and may resort to other options, like load curtailment, load shifting, etc. to keep its operational feasibility.

Figure 1.2 depicts a typical configuration of Microgrids. In figure 1.2, CHP means combined heat and power and PCC is a reduction for the point of common coupling.

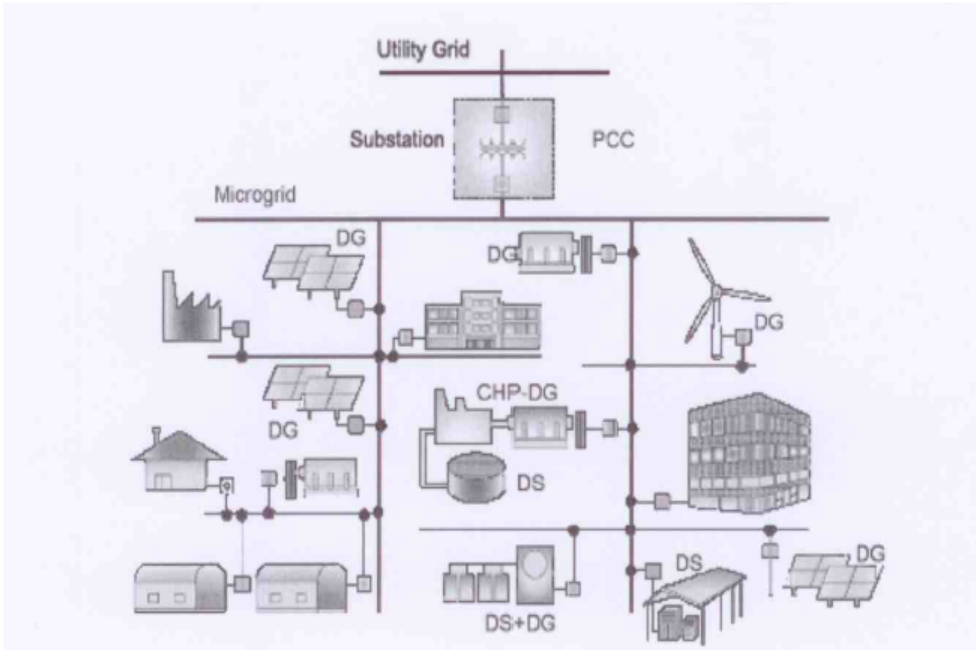

Figure 1.2. Typical Configuration of Microgrid [6]

1.2 Microgrid Types

Microgrids can be classified into different groups based on the type (such as campus, military, residential, commercial, and industrial), the size (such as small, medium, and large scales), the application (such as premium power, resilience-oriented, loss reduction, etc.), and the connectivity (remote and grid-connected)[7]. Based on the voltages and currents assumed in a microgrid, however, three microgrid types can be classified: AC, DC, and hybrid. In AC microgrids, all DERs and loads are connected to a common AC bus. DC generating units as well as energy storage will be connected to the AC bus via DC-to-AC inverters, and further, AC-to-DC rectifiers are used for supplying DC loads. In DC microgrids, however, the common bus is DC, where AC-to- DC rectifiers are used for connecting AC generating units, and DC-to-AC inverters are used for supplying AC loads. In hybrid microgrids, which could be considered as a combination of AC and DC microgrids, both types of buses occur, where the type of connection to each bus depends on the closeness of the DER/load to the bus. Different characteristics of microgrids operation and control found in immense studies, where the majority of these studies focus on AC microgrids, perceivably due to the connection to the AC utility grid and the utilization of AC DERs. There are some advantages for DC microgrid after you compared with AC microgrids: 1) higher efficiency and reduced losses due to the reduction of multiple converters used for DC loads, 2) easier integration of various DC DERs, such as energy storage, solar PV, and fuel cells, to the common bus with simplified interfaces, 3) more efficient supply of DC loads, like electric vehicles and LED lights, 4) eliminating the need for synchronizing generators, which enables rotary generating units to operate at their own optimum speed, and 5) enabling bus ties to be operated without the need for synchronizing the buses [8]. These advantages, combined with the considerable increase in DC loads such as personal computers, laptop computers, LED lights, data and telecommunication centers, and other applications where the typical 50-Hz and 60-Hz AC systems are not available, could potentially introduce DC microgrids as viable and economic solutions in addressing future energy needs.

The previous research on DC microgrid planning is rather limited and available studies on microgrid planning mostly focus on AC microgrids. The study in [9] proposes a planning model for AC microgrid considering uncertain physical and financial information. The microgrid planning problem is broken down into an investment problem and an operation subproblem. The optimality of the solution is examined by employing the optimal planning decisions obtained from the master problem in the subproblem under uncertain conditions. The study in [10] suggests an operation modeling of hybrid AC-DC microgrids. It explains that the operation model of such hybrid microgrid consists of system and device levels. This model includes advantages of both AC and DC microgrids, and performs both optimal scheduling and voltage control. The study in [11] proposes an operation planning model considering load/generation changes for a low voltage DC microgrid including DC sources like battery, fuel cell, and PVs. The objective of the study is to minimize daily operation costs. The model utilizes a multi-path dynamic programming approach to solve the problem. The study in [12] presents a multi-objective optimal scheduling of a DC microgrid consisting of a PV system and an electric vehicle charging station. In this study, the cost of electricity and energy circulation of storage are taken as objective functions, and the mathematical model is built and solved to obtain the Pareto optimal solution. The study in [13] investigates a control system for hybrid AC-DC microgrids connected by multilevel inverters. The droop control technique is offered to manage power flows between AC microgrid, DC microgrid, and the main grid. The study in [14] discusses the power management in a hybrid AC-DC microgrid and proposes an interlinking AC-DC converter accompanied by a suitable control system. The power flow between different sources throughout both microgrids is controlled. The hybrid AC-DC microgrid allows different loads and DERs to connect with the minimum need for electrical conversion, which decreases the cost and energy losses. The study in [15] states that the efficiency of distributed generations and energy storage systems in a microgrid might reduce because of microgrid operation, therefore running some consumers into problem. This study proposes an optimized operation planning for distributed generations and energy storage systems in microgrids to solve this issue.

The microgrid designer is planning to organize a microgrid, however, the challenge is to characterize the type of the microgrid, i.e., either AC or DC, based on the system characteristics and accordingly determine the optimal DER generation mix.

1.3 Emergence of Microgrids

The advent of modern distribution networks with DERs has changed the service restoration example. Such distribution networks are equipped with local generation sources that behave like virtual power plants and active loads that provide ancillary services such as frequency and voltage support and service restoration to the utility [16]. Under such conditions, the operation of the distribution network necessitates enhanced protocols for communication at all levels of the distribution system to assist distribution management system (DMs) operators with real-time decisions.

Smart distribution systems establish microgrids and apply smart grid to the establishments for managing 1) DERs and storage technologies, 2) demand-responsive proactive consumers, and 3) decentralized control of energy resources and distribution feeders resulting from the formation of microgrids [17]. Microgrids are often connected to distribution feeders and offer load and generation control to provide continuity of supply in the event of utility grid disturbances. Such microgrid control has a hierarchical structure for enhancing the security, controllability, and exibility of distribution network operations. Microgrids can be operated in a grid-connected mode, in which their loads are partially supplied by the distribution system, or in an island mode, in which the local generation supplies the entire microgrid load in case of a major outage at the utility distribution system. A microgrid has its own energy management system for the control of its DERs and for devising demand-response strategies. As a result, a microgrid can behave as an active load in a distribution network that can also be isolated from the rest of network. By incorporating available microgrids in load restoration procedures, the distribution utility can improve its load restoration capability and further enhance distribution system reliability.

In a modern distribution system, microgrids are regarded as reliable alternatives to more traditional methods of restoring deenergized areas of distribution systems and providing secure energy resources to local entities until the utility grid is restored. A decentralized power grid can use microgrids to isolate a neighborhood in the event of disasters and serve critical systems and buildings like data centers, hospital communities, and campuses by utilizing local generation and storage facilities [16].

The technologies incorporated in microgrids are developing, and real-world examples have been deployed in various countries. Honeywell's White oaks project in Maryland is an example of deployed microgrids in the United States; the microgrid supplied power to local systems during a summer storm in 2012. Synergetic thinking is a crucial part of improving the economics of microgrids and lowering the cost of energy in general rather than focusing only on electricity. Up-front planning for serving customer loads could increase microgrid energy efficiency to more than 75%. Depending on its capacity, a microgrid can provide ancillary services such as frequency and voltage support by injecting power into the grid. The sendai 1-MW microgrid at tohoku fukushi university in Japan is an example of a university microgrid. It operated for two days in island mode during the March 2011 earthquake and tsunami while the surrounding region was without power [17]. Their unique characteristics make microgrids suitable candidates for service restoration duty in power distribution networks.

CHAPTER 2

AC MICROGRID

AC microgrids represent the most deliberated microgrid structure. In AC microgrids, all DERs and loads are connected to a common AC bus. General studies can be found on different aspects of microgrids operation and control, where the majority of these studies focus on AC microgrids, perceivably due to the connection to the AC utility grid and the utilization of AC DERs.

There are some benefits for AC microgrids, which we can be classified as:

- Easy to set up; requires only 3 connecting points (Battery, PV panels, Loads)
- Clean and safe energy
- Built in safety features (Human and equipment protection)
- Minimum maintenance
- 24/7 energy supply
- Designed specifically for off-grid, rural applications
- Robust, suited to harsh environments
- Intelligent, optimizes and maximizes energy production and protects batteries
- Supervision could be provided in high range

2.1 System Layout

An AC microgrid is an interconnection of domestic distributed loads and low voltage distributed energy sources, such as microturbines, wind turbines, PVs, and storage devices. Simplified AC microgrid architecture is shown in Figure 2.1. This microgrid consists of a group of radial feeders as a part of a distribution system. The domestic load can be divided to sensitive/critical and nonsensitive/noncritical loads via separate feeders. The sensitive loads must be always contributed by one or more microsources, while the nonsensitive loads may be shut down in case of contingency, or a serious disturbance.

The central controller manages each unit's feeder by a power flow controller. The circuit breaker is used to disconnect the correspondent feeder (and associated unit) to avoid the impacts of sever disturbances through the microgrid. The AC microgrid can be connected to the distribution system by a point of common coupling (PCC) via a static switch (SS). The static switch is capable to island the microgrid for maintenance purposes or when faults or a contingency occurs.

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

The microsources and storage devices use power electronic circuits to connect to the AC microgrid. Usually; these interfaces depending to the type of unit are AC/AC, DC/AC, and AC/DC/AC power electronic converters/inverters. As the microgrid elements are mainly power-electronically interfaced, the microgrid control depends on the inverter control.

For increasing reliability in the conventional power systems, the microgrid systems must be able to have proper performance in both connected and disconnected modes. In connected mode, the main grid is responsible for controlling and maintaining power system in desired conditions and, the microgrid systems act as real/reactive power injectors. But in disconnected mode, the microgrid is responsible for maintaining the local loads and keeping the frequency and voltage indices at specified nominal values [93], [94], [95].

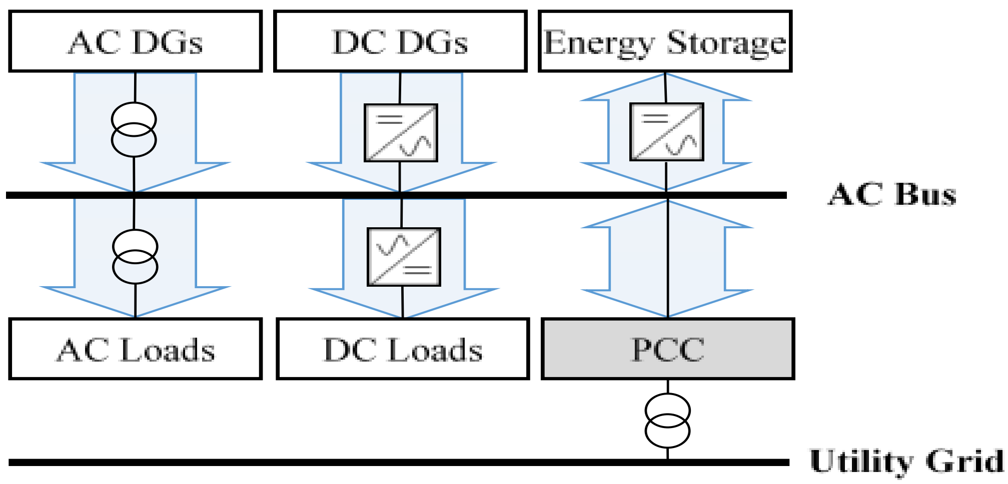

Figure 2.1. General structure of AC microgrid [96]

2.2 Planning

Microgrid scheduling problem purposes at minimizing the operation costs of local DERs, as well as the power exchange with the utility grid, to supply forecasted microgrid loads in a definite period of time (typically one day). The microgrid scheduling problem is subject to a variety of operational constraints such as energy balance, load management, and DER limitations. An optimal model predictive control-based strategy for the multi-objective optimization problinem is proposed in [18] with the goals of minimizing fuel costs and changes in power output of diesel generators, minimizing costs associated with low battery life of ESS, and maximizing the ability to maintain real-time power balance during operations. In [19], two new cost-prioritized droop schemes are developed to reduce the microgrid total generation cost. They operate by tuning the dispatch priorities of DGs and curve shapes of their resulting active power versus frequency plots. In [20], a knowledge based system controller is used to schedule a wind-diesel-ESS isolated microgrid an hour ahead so that the diesel generator power is reduced and fuel cost is minimized. A scheduling model for a residential microgrid considering temperature dependent thermal load in the model facilitating a combined heat and power control [21].

The microgrid scheduling problem can be examined from two major perspectives: scheduling architecture and methodology. In the background of the scheduling architecture, the existing Energy Management System (EMS) architectures for microgrids are reviewed in [22] and [23], where centralized and distributed models are identified as common microgrid scheduling schemes. The scheduling problem can be solved centrally in a central computing unit, able to access generation and load information and dispatching generation according to total load demand and individual generator's cost curve [24]-[31]. In [24], a centralized control system that coordinates parallel operations of different DG inverters within a microgrid is proposed, employing a model predictive control algorithm that optimizes the steady-state and transient control problems separately. The large number of control devices requires higher capacity of communication network and higher computational capability, which would act as a barrier for employing the microgrid centralized control. The study in [25] proposes control software aiming to provide advice to power system operators regarding scheduling of resources in an islanded system. In [26], a scheduling approach for a hydrogen storage system is presented. The microgrid scheduling problem is solved by differential evolution approach [27]. In [28], a scheduling scheme is proposed for a microgrid, including advanced PV generators with embedded ESS and gas microturbines. The scheduling is performed in two parts: a central energy management and a local power management at the customer side. The study in [31] proposes a scheduling model for microgrids considering uncertain islanding. The problem is decomposed into normal and islanded problems and islanding cuts are used to revise the schedules to ensure feasible operation.

In the distributed model, however, each component is considered as an agent with the ability of discrete decision-making, and the optimal schedule is obtained using iterative data transfers among agents [32]-[39]. In [37], consensus theorem is used in a decentralized multi-agent platform. In [38], the dual decomposition method is utilized to decompose the original problem into smaller subproblems solved by controllers of DGs, dispatchable loads, DES, and renewable energy sources. Each control scheme offers its own benefits and drawbacks, but the centralized model is commonly more desirable as it ensures a secure microgrid operation and is more suitable for the application of optimization techniques. The main drawbacks of the centralized scheme are reduced flexibility in adding new components and relatively extensive computational requirements [22]. The study in [39] presents a nonlinear droop scheme for power sharing in a microgrid with different types of DGs aiming at reducing total microgrid generation cost. The study in [36] presents a model to simulate closed loop price signal control optimal power flow (OPF) by a microgrid central controller. The central operator only influences the decision taken by each unit via price signals. Dispatch decision is decentralized to each controllable unit increasing system capability to cope with a large number of generating units. A range of case studies shows the approach's ability to handle small and large scale disturbances both within and outside the microgrid. Optimization is used by an advanced Primal Dual Interior Point Method based on Nonlinear Programming.

Available software to solve the microgrid scheduling problem include WebOPT [40] and HOMER [41]. WebOPT is a mixed integer linear programming (MILP) optimization program for planning purposes developed using General Algebraic Modeling System. HOMER software is used for simulation, optimization and sensitivity analysis of microgrids. In [42], a simulation platform is presented for the modeling and study of microgrids using MathWorks Simulink modeling software, providing a library of tools for designing and simulating the behavior of a microgrid on time scales from seconds to days which includes a collection of power system and power electronics components that may be arbitrarily configured.

In the context of the scheduling methodology, a variety of approaches are proposed to solve the microgrid scheduling problem, including deterministic, heuristic, and stochastic methods. Deterministic methods include advanced primal dual interior point method based on nonlinear programming [36], sequential quadratic programming [43], MILP [70], [71], [44]-[50], subgradient search [51], reduced gradient search [52], quadratic programing and linear programing [38], [53], and interior point method [54]. The MILP is a modification of standard integer programming that treats the objective and constraint functions as continuous, and some variables as integers. In dynamic programming, the problem is decomposed into a series of smaller problems, and an optimal solution is developed to the original problem step-by-step. The optimal solution is recursively developed from the subproblems. Its fundamental form examines every possible state in every interval and rejects infeasible ones. Dynamic programming methods typically suffer from the curse of dimensionality. Lagrangian relaxation decomposes the problem into a master problem and a number of manageable subproblems, which would be solved separately. Lagrangian multipliers that are added to the master problem to yield a dual problem link the subproblems. The dual problem has lower dimensions than the primal problem and is easier to solve. The difference between the two functions yields the duality gap for which the primal function is an upper bound. This gap provides a measure of the optimality of the solution. It is more flexible for handling different types of operating constraints in a power system and has higher computational efficiency compared to other methods. It can be easily extended to incorporate various constraints. Its main drawback is the inability to guarantee the solution feasibility and convergence [55]. In [56] a non-linear mixed integer programming problem is decomposed into integer and continuous variable optimizations and the continuous problem is solved using successive dynamic programming. In [49] models of an energy supply chain network are proposed in an MILP framework based on small-scale micro-generation through combined heat and power systems aiming at minimizing operation and trade costs under full energy demand satisfaction. In [57], the microgrid economic scheduling is posed as an MILP model. No complex heuristics or decompositions are used leading to significant improvements in scheduled quality and in computational burden. Unit commitment, economic dispatch, ESS, sale and purchase of energy to/from the utility grid, as well as curtailment schedule are considered. The study in [50] presents an optimal dispatching strategy of microgrid-based ESS, which also includes wind generator, PV system, fuel cell, micro turbine, and diesel generator. Results show that a battery switch station can bring more profit and reserve for the microgrid than other types of ESS.

PSO is the most common heuristic method in solving the microgrid scheduling problem. It can be applied to global optimization problems with nonconvex or nonsmooth objective functions. PSO is easy in its concept and implementation by having only a few parameters to adjust. It can solve problems with high-quality solutions within relatively shorter calculation times and more stable convergence characteristics than other stochastic methods [74]. Differential evolution can handle optimization problems with nonsmooth/nonconvex objective functions. It has a simple structure and a good convergence property, and requires a few robust control parameters, but takes a relatively longer computation time to achieve the final solution [76]. In [63], an EMS is proposed to optimally coordinate the power production of DG sources and ESS to minimize the operational costs of microgrids. A matrix real-coded GA optimization module is used to achieve a practical method for load management. In [78], a multi-objective optimization model is presented to minimize the power generation cost and to maximize the useful life of lead-acid batteries via the nondominated sorting GA. Results show that the proposed method can optimize the system operations under different scenarios and help users obtain the optimal operation schemes. The study in [65] shows how different optimal output sets of DER-mix, operating within their respective capacity limits, could economically share an electrical tracking demand among micro-turbines and diesel generators of various sizes. It satisfies different heat demands, on the basis of multi-objective optimization, compromising between fuel cost and emission. Optimization is done using differential evolution technique under real power demand equality constraint, heat balance inequality constraint, and DER capacity limits constraint. In [69], improved fast evolutionary algorithm is applied to determine the economic load sharing scenario in a typical microgrid by minimizing the cost incurred for operation, maintenance, and emissions. Results reveal that the developed technique is easy to implement, has converged within an acceptable execution time, and yields highly optimal solution for combined economic and emission dispatch with the minimum operation and emission costs. The study in [77] proposes an operation optimization model based on the multi-cross learning-based chaotic differential evolution algorithm, which has a higher exploration capability compared to PSO and gravitational search.

Stochastic methods are primarily used to handle prevailing uncertainties in the microgrid scheduling process. In [73], a stochastic programming method is adopted to address the scheduling of a reconfigurable lithium ferrophosphate battery to improve the reliability and economic performance of the microgrid. Chance-constrained programming is utilized to consider the random wind power, PV power, as well as thermal and electric load in the optimal schedules of a combined heat and power system [78]. The study in [79] presents a scheduling of autonomous generators, renewable resources, ESS devices, and schedulable loads in a microgrid for buildings. The problem is formulated as stochastic optimization and solved by a scenario tree method. It is shown that for this problem even in the presence of uncertainties, the deterministic model based on forecasts of demand and renewable generation offers an efficient equivalence to the stochastic model. The study in [82] formulates the same stochastic optimization problem considering uncertainties in demand profiles and solar radiation, and solves it using a scenario tree method. It attempts to find the optimal ESS capacities and operating plan in a building energy system. It is found that thermal ESS units and water tanks are effective in saving the energy cost in all scenarios, but the electrical battery may not be economical to use due to its high investment cost and short lifetime. It is found that it would be sufficient in many cases to obtain the best combination of ESS devices with the forecasted demand and solar radiation, without using stochastic formation.

In addition to deterministic, heuristic, and stochastic methods, hybrid methods, which benefit from a combination of two or more methods, are proposed and used in the microgrid scheduling. A hybrid of evolutionary programming and hill climbing techniques is used in [80]. In [81], a bi-level prediction strategy for short-term load forecast of microgrids is presented. The upper level uses the enhanced differential evolution optimizing the adjustable parameters of the feature selection method with the forecast engine in the lower level. The hybrid forecast engine is composed of the neural network and evolutionary algorithm.

There are some decisive factors in microgrid scheduling, including market price, emission consideration, and power flow in microgrids. In the context of electricity price, there are two common types of pricing: flat rates and time-based rates. Under flat rate pricing, customers pay a fixed charge per KWh of electricity consumed independent of the time of usage, thus flat rates are unvarying. Flat rates are often assigned to residential customers, and are the only option in the absence of meters that can record time-differentiated usage (except block rates). A range of time-based rates is currently offered directly to retail customers, including time of-use pricing (TOU), real-time pricing (RTP), and critical peak pricing (CPP). In TOU, a rate with different unit prices is defined for electricity usage during different blocks of time, typically for a day. TOU rates reflect the average cost of generating and delivering power during those time periods. TOU rates often vary as a function of time of day (e.g., peak vs. off-peak period) and season, and are typically pre-determined for a period of several months or years.

TOU rates are in widespread use for large commercial and industrial customers. TOU rates require meters that register cumulative usage during the designated time blocks. In RTP, the electricity price typically fluctuates hourly reflecting changes in the wholesale price of electricity. Forecasted RTP prices are typically made available to customers on a day ahead or hour-ahead basis. CPP rates include a pre-specified high rate for usage designated by the utility in a critical peak period, and may be triggered by system contingencies or high prices paid by the utility for procuring power from wholesale electricity markets. CPP rates are not yet common, but have been tested in pilots for large and small customers in several states [83], [84]. In [85] the problem of energy imbalance management in a microgrid is studied from the market perspective. The paper proposes a pricing scheme that provides robustness against intermittent power inputs. It is shown that the parameters can be obtained by solving a linear matrix inequality problem, which is efficiently solvable due to its convexity. The underlying idea is to use fuzzy systems together with a linear matrix inequality approach to assure the robustness of market dynamics. The proposed design outperforms the existing area control error pricing scheme by managing the imbalanced energy more quickly, and also being robust against system disturbances. In [86], a nonlinear optimal model of cogeneration microgrid is presented to deal with the economic operation of available power resources, which formulates a 24-hour work schedule. Test results indicate that the peak-valley energy price would increase the system operation costs, while using battery and peak load shifting can effectively reduce operation costs. In [87], an economic investment model is presented for microgrid operators to optimize their profits in a competing market formed by the utility company, subject to environmental policies. The microgrid operators play a Nash game in the market. The analyses show that the utility company has the flexibility to adjust the Nash Equilibrium of lower level microgrid optimization problems by changing the electricity price and energy arbitrage market demand.

Emission consideration is another important issue that has been noticed in several proposed microgrid scheduling problems. In [46], emissions are minimized within the optimization framework. In [44], the operation plans of a microgrid fewer than three objectives including minimization of the annual cost, CO_2 emissions, and primary energy consumption are studied. In [46], a weighted average of energy costs and CO_2 emissions in zero-net-energy commercial buildings is minimized. In [54], atmospheric pollutants, such as sulfur oxides (SO_2), carbon dioxides (CO_2), and nitrogen oxides (NO_x) caused by fossil-fueled thermal units, are considered as the environmental cost in the scheduling optimization problem. In [88], an optimization model for the optimal energy management of microgrids in commercial buildings is presented to increase the efficiency of energy utilization, minimize operational costs, and reduce environmental impacts of energy utilization. It was shown that by using the developed multi-objective optimization approach, total daily energy costs and greenhouse gas emissions of these microgrids could be significantly reduced as compared to nonintegrated baseline solutions.

Although the microgrid size is much smaller than the utility grid and also the congestion in the microgrid network is less probable, the issue of power flow in microgrids has been discussed in some publications with the primary objective of preventing voltage volatilities and ensuring the microgrid reliable operation. The study in [89] proposes an OPF solution that considers the entire system: the ESS device limits, voltages limits, currents limits, and power limits. The power network may be arbitrarily complex, and the proposed solver obtains an optimal solution. The method combines a power flow solver with a dynamic programming recursive search, achieving a numerically efficient solution. This combination is robust and numerically efficient and reveals the optimal stored energy versus time for each ESS device. The study in [90] presents a Newton Raphson equation for the solution of power flow analysis in microgrid, comprising 2n current injection equations and active power equations for a system with n buses including one slack bus and m generator buses. The reactive power mismatch of the generator bus is introduced as a new state variable, which leads to a simple procedure for converting bus model between the generator bus and the load bus. The proposed method is also applied to other occasions where the polar coordinates are adopted. The study in [91] considers the OPF for microgrids, with the objective of minimizing either power distribution losses or the cost of power drawn from the substation and supplied by DGs leading to voltage regulation. A semi-definite programming (SDP) relaxation technique is advocated to obtain a convex problem solvable in polynomial-time complexity. Numerical tests demonstrate the ability of the proposed method to obtain an optimal solution of the original nonconvex OPF. To ensure scalability with respect to the number of nodes, robustness to isolated communication outages, and data privacy and integrity, the proposed SDP is solved in a distributed fashion by resorting to the alternating direction method of multipliers. The resulting algorithm entails iterative message-passing among groups of consumers and guarantees faster convergence compared to competing alternatives. Another approach is proposed in [92] to use an equivalence for converters in an AC-to-DC network to replace the DC microgrids with AC microgrids, solve the OPF problem of the equivalent AC network using semi-definite programming, and then use it to determine the solution of the original OPF problem.

2.3 Operation and Control

Microgrids operate in two modes of grid-connected and islanded. In the grid-connected mode, microgrids trade power with the utility grid. In the islanded mode, however, the microgrid operates autonomously without connection to the utility grid. Because of characteristics of the microgrid such as two-way power transfer, presence of DGs, DSM, and considerable presence of power electronics, control of the microgrid in each operation mode as well as the switching between the modes are of the challenges that need to be solved to use microgrids efficiently and realize their features.

Inverters can provide the control and flexibility required for plug-and-play functionally. Microgrid controls need to insure that; new microsources can be added to the system without modification of existing equipment, the Microgrid can connect to or isolate itself from the grid in a rapid and seamless fashion, reactive and active power can be independently controlled, and can meet the dynamic needs of the loads.

Microsource controller techniques described below rely on the inverter interfaces found in fuel cells, microturbines, and storage technologies. A key element of the control design is that communication among microsources is unnecessary for basic Microgrid operation. Each microsource controller must be able to respond effectively to system changes without requiring data from the loads or other sources.

Operation of the Microgrid assumes that the power electronic controls of current microsources are modified to provide a set of key functions, which currently do not exist. These control functions include the ability to; regulate power flow on feeders; regulate the voltage at the interface of each microsource; ensure that each microsource rapidly pickups up its share of the load when the system islands. In addition to these control functions the ability of system to island smoothly and automatically reconnect to the bulk power system is another important operational function. Figure 2.2 is a block diagram of the microsource controller. The critical system performance components are the voltage versus reactive power droop and power versus frequency droop.

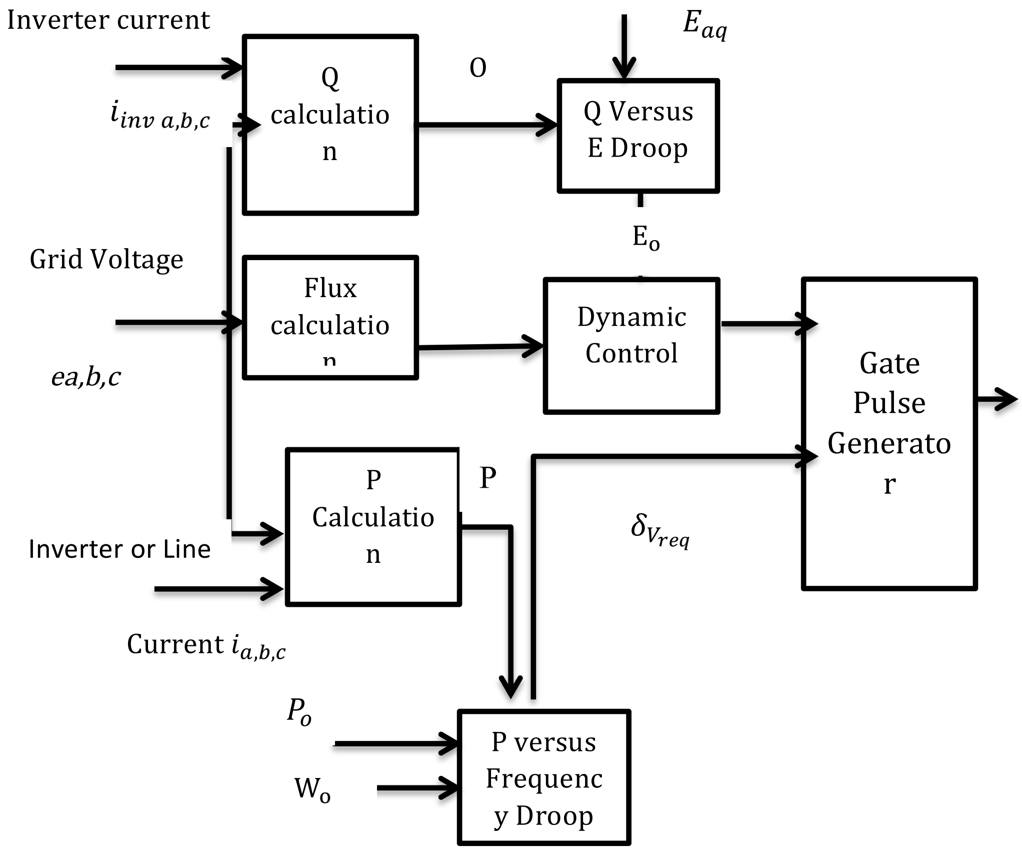

Figure 2.2. Microsource Controller [99]

- Voltage Vs. Reactive Power (Q) Droop: Integration of large numbers of microsources into a Microgrid is not possible with basic unity power factor controls. Voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must also insure that there are no large circulating reactive currents between sources. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased.

- Power Vs. Frequency Droop: Microgrids can provide premium power functions using control techniques where the Microgrid can island smoothly and automatically reconnect to the bulk power system, much like a UPS system. In island mode, problems from slight errors in frequency generation at each inverter and the need to change power-operating points to match load changes need be addressed. Power vs. frequency droop functions at each microsource can effectively solve these problems without a communication network. When the Microgrid is connected to the grid, Microgrid loads receive power both from the grid and from local microsources, depending on the customer's situation. If the grid power is lost because of voltage drops, faults, blackouts, etc., the Microgrid can transfer smoothly to island operation. When the Microgrid separates from the grid, the voltage phase angles at each microsource in the Microgrid change, resulting in an apparent reduction in local frequency. This frequency reduction coupled with a power increase allows for each microsource to provide its proportional share of power.

2.3.1 Microgrid Control For Islanded Operation. Islanding of the microgrid can take place by unplanned events like faults in the MV network or by planned actions like maintenance requirements. The local generation profile of the microgrid can be modified in order to reduce the imbalance between local load and generation and reduce the disconnection transient [98]. In the presence of unplanned events like faults, microgrid separation from the MV network must occur as fast as possible. However, the switching transient will have great impact on microgrid dynamics.

If there are no synchronous machines to balance demand and supply, through its frequency control scheme, the inverters should also be responsible for frequency control during islanded operation. In addition, a voltage regulation strategy is required; otherwise, the microgrid might experience voltage and/or reactive power oscillations [99]. If a cluster of MS is operated within a microgrid and the main power supply (the MV network) is available, all the inverters can be operated in PQ mode, because there are voltage and frequency references. In this case, a sudden disconnection of the main power supply would lead to the loss of the microgrid, since there would be no possibility for load/generation balancing and therefore for frequency and voltage control. However, by using a VSI to provide a reference for voltage and frequency, it is thus possible to operate the microgrid in islanded mode, and a smooth moving to islanded operation can be performed without changing the control mode of any inverter [100]. As previously described, the VSI can react to network disturbances based only on information available at its terminals. This working principle of a VSI provides a primary voltage and frequency regulation in the islanded microgrid. After identifying the key solution for microgrid islanded operation, two main control strategies are possible: a) single master operation (SMO) or b) multi master operation (MMO). In both cases, a convenient secondary load-frequency control during islanded operation must be considered to be installed in controllable MS.

2.3.1.1 Single Master Operation. A general overview of an SMO is shown in Figure 2.3. In this case, a VSI—acting as master—can be used as voltage reference when the main power supply is lost being that all the other inverters operated in PQ mode (slaves). Local MS controllers can receive information from the MGCC about the generation profile and control accordingly the corresponding MS.

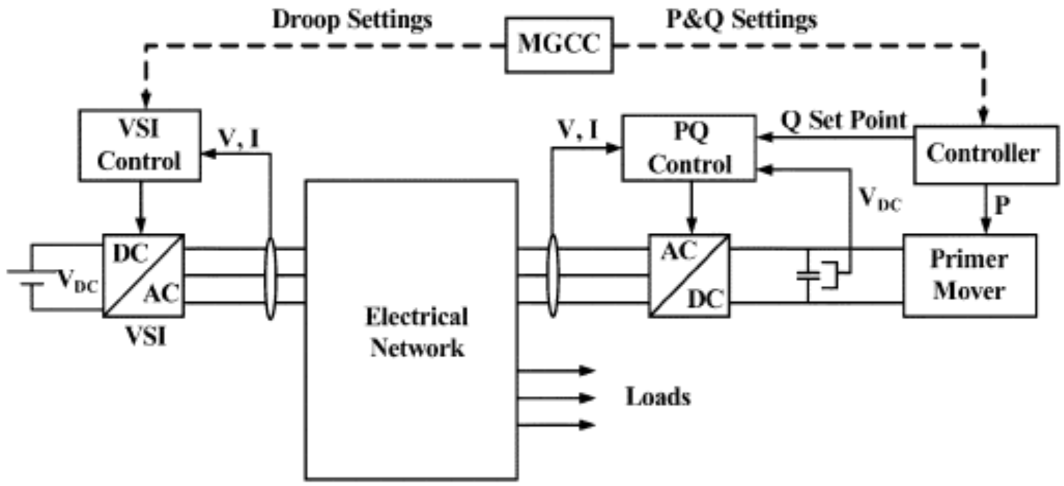

Figure 2.3. Control Scheme for SMO [97]

2.3.1.2 Multi Master Operation. As described in Figure 2.4, in a multi master approach, several inverters are operating as VSI with pre-defined frequency/active power and voltage/reactive power characteristics. The VSI can be coupled to storage devices (batteries or flywheels) or to MS with storage devices in the dc-link (batteries, super capacitors), which are continuously charged by the primary energy source. Eventually, other PQ-controlled inverters may also coexist. The MGCC can modify the generation profile by changing the idle frequency of VSI and/or by defining new set points for controllable MS connected to the grid through PQ-controlled inverters.

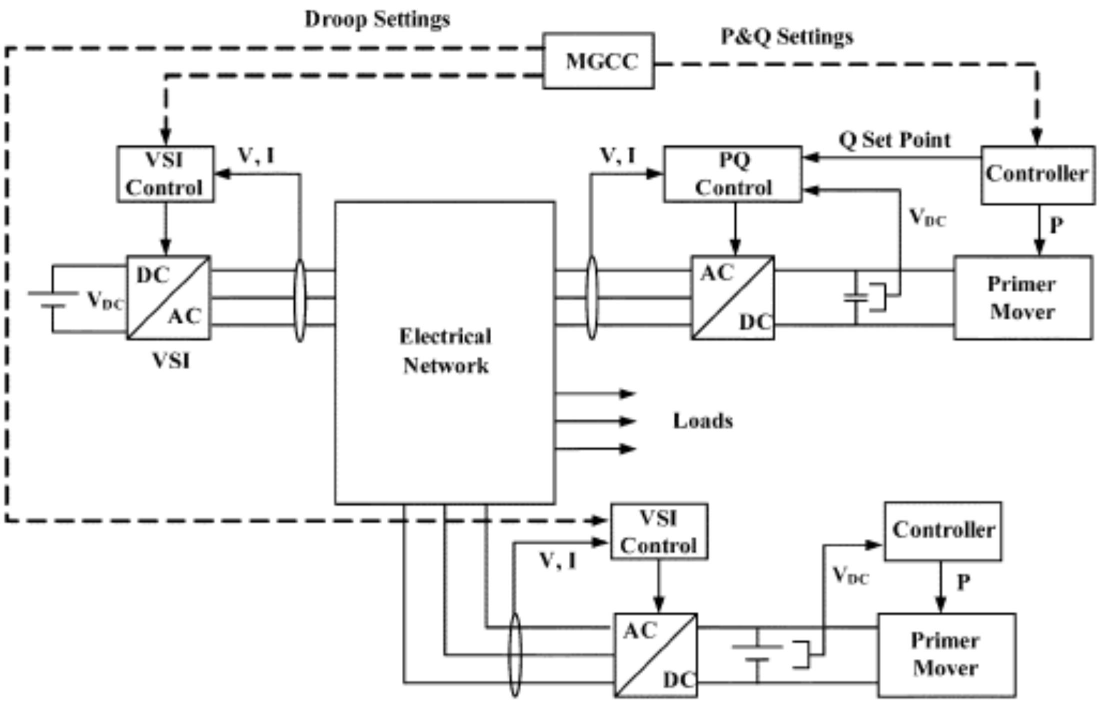

Figure 2.4. Control Scheme for MMO [97]

2.3.1.3 Secondary Load-Frequency Control. Equation (1) shows that the VSI active power output is proportional to the microgrid frequency deviation. If the microgrid frequency stabilizes in a value different from the nominal one (due to the use of only proportional droop controls), storage devices would keep on injecting or absorbing active power whenever the frequency deviation differs from zero. This should be only admissible during transient situations, where storage devices are responsible for the primary load-frequency control. Storage devices (batteries or flywheels with high capabilities for injecting power during small time intervals) have a finite storage capacity and can be loaded mainly by absorbing power from the LV grid. Therefore, correcting permanent frequency deviations during any islanded operating conditions should then be considered as one of the key objectives for any control strategy.

$$\Delta w = W_{Oi} - K_{pi}\times P_i - \left[W_{Oi} - K_{pi}\times(P_i + \Delta P_i)\right] = K_{pi}\times\Delta P_i \quad (1)$$

In order to promote adequate secondary control aiming to restore frequency to the nominal value after a disturbance, two main strategies can be followed: local secondary control, by using a PI controller at each controllable MS (Figure 2.5) or centralized secondary control mastered by the MGCC. In both cases, target values for active power outputs of the primary energy sources are defined based on the frequency deviation error [101]. For SMO, the target value is directly an active power set-point sent to the prime mover of a controllable MS, while for MMO, the target value can be both an active power set-point for a controllable MS connected to a PQ inverter or a new value for the idle frequency of a VSI.

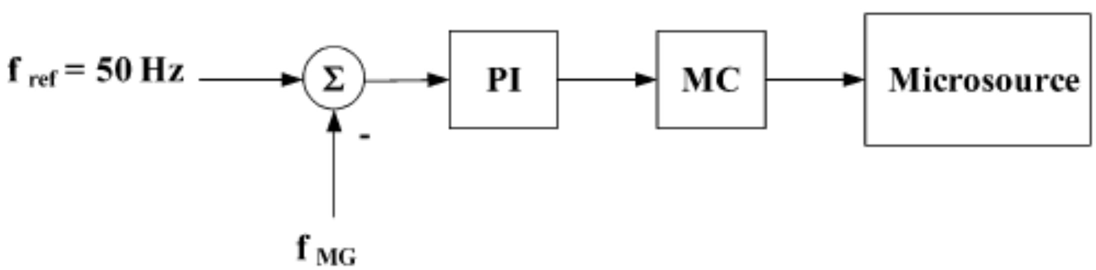

Figure 2.5. Local Secondary Load-Frequency control for controllable microsources [97]

2.4 Communications

The role of communication systems in the microgrid is to provide a means to exchange data and monitor various elements for control and protection purposes. In a centrally controlled microgrid, the communication network is necessary to communicate control signals to the microgrid components. In a microgrid with the distributed control, the communication network enables each component to talk with other components in the microgrid, decides on its operation, and further reaches predefined objectives [102]. Communications within the microgrid is necessary to enable a rapid fault clearing an increasing efficiency in islanding incidences. Despite its significant role in developing efficient and advanced microgrids, no review on microgrid communications is currently available.

The study in [103] proposes the establishment of a wireless network to acquire the information of total real and reactive power generation of all DGs in order to enhance the microgrid stability. In [104], a microgrid test-bed is proposed to investigate cognitive radio networks in the fifth generation wireless technology. The technique of independent component analysis with robust principal component is applied to smart meter wireless data recovery. In [105], heterogeneous wireless network architecture has been established to set up a multi-agent coordination between DGs to make decisions in a decentralized economic dispatch. In [106], a communications algorithm is proposed based on the consensus theorem as a solution for economic dispatch of DGs in a decentralized multi-agent platform. The study in [107] asserts that for power sharing improvements amongst DGs in weak system conditions, the web-based low bandwidth communication is more economic and justiable than costly advanced high bandwidth communications. In [108], an optimization scheme providing online set-points for each DG, operation modes for a water supply system, and signals for consumers based on a DSM mechanism through a SCADA system is proposed. In [109], a secure energy routing mechanism is proposed that detects most internal attacks by using message redundancy during topology discovery. In [110], a semantic overlay network is presented that allows to efficiently route queries related to microgrid control in the overlay network, based on an XML description of the static and dynamic characteristics of the intelligent electronic devices. The dynamic structure of the microgrid, which may change at each instant, requires that connections in the microgrid be monitored and the relay hierarchy be reset. In [111], a reliable overlay topology design scheme is presented that maximizes the usage of renewable energy in the microgrid and applies survivability approaches borrowed from high-speed networks to microgrids. In [112], a DC microgrid with multi-layer control and smart grid communications is proposed; enabling better DC microgrid integration and providing possibility to reduce the negative impact on the utility grid by using the supervision interface. The power balancing control interface provides possibility for advanced energy management with low speed communication. The study in [113] proposes a distributed energy management strategy based on the power line communication in a DC microgrid.

CHAPTER 3

DC MICROGRID

Microgrids are divided into AC microgrids, DC microgrids, and hybrid AC/DC microgrids depending on whether distributed generation (DG) and loads are connected on the basis of an AC or DC grid. AC microgrids have the benefit of utilizing existing AC grid technologies, protections and standards. However, there are several benefits associated with the utilization of DC microgrids, such as synchronization, stability, and the need for reactive power. DC microgrids also satisfy the demands of today since most environment-friendly DGs, such as photovoltaic, fuel cells and variable speed wind power systems generate DC power and most digital loads require DC power. In addition, DC microgrids can eliminate the DC-AC or AC-DC power conversion stages required in AC microgrids for the above renewable energy sources and loads. Therefore, they have advantages in terms of efficiency, cost and system size. However, DC microgrids need further research on the proper operating range of DC voltage and protection apparatus for DC circuits.

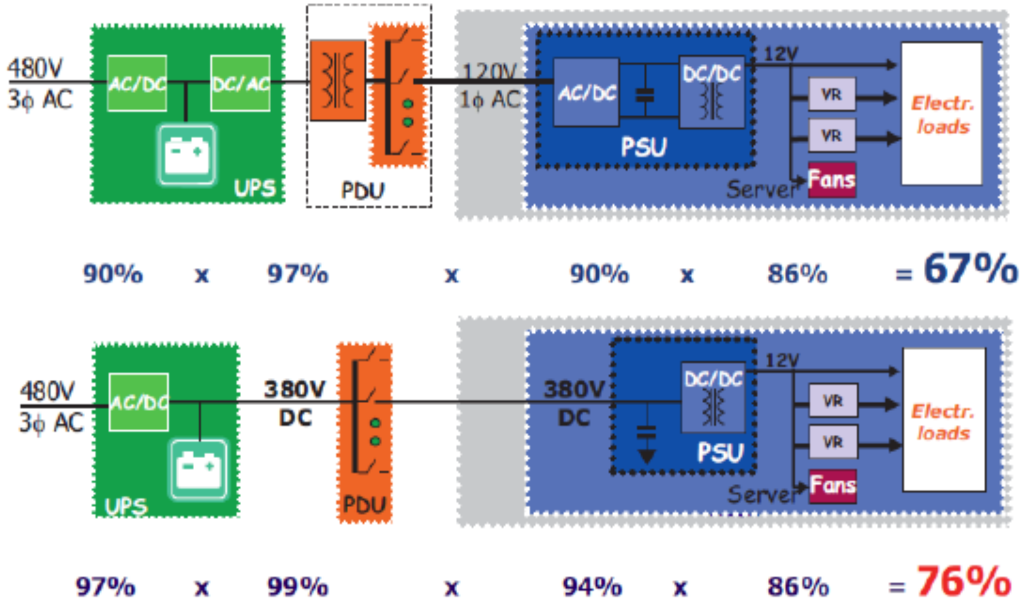

Figure 3.1. AC Vs. DC microgrid

3.1 System Layout

Typical DC microgrid systems are reviewed here. In general, the topologies of DC microgrids can be classified into three categories: single-bus topology, multi-bus topology and reconfigurable topology.

3.1.1 Single-bus Topology. Single-bus topology is commonly used for DC microgrids, and it can be regarded as the basis of multi-bus systems. Figure 3.2 shows an exemplary schematic diagram of the most common type of DC microgrids, which is frequently deployed in practical industrial applications. It is based on the singular DC bus to which energy storage systems (ESS) are directly connected to [114]–[117]. The number of series battery cells is determined depending on the voltage required by loads. Electrical power supply systems for telecom applications have been historically using this configuration operating at 48V [118]. Many types of converters that can be seamlessly connected to the bus operating around this nominal voltage are available in the market.

However, despite inherent dynamic stability of the system, an uncontrollable voltage in the common DC bus, which depends mostly on the state of charge (SoC) and current of the battery, limits its application only to dense, singular bus systems. Apart from that, it suffers from the practical problem of unregulated battery charging, as it needs to be performed coordinately by a number of paralleled converters that have inherent imperfections in bus voltage measurement. This causes a circulating current problem that leads to uneven loading of those converters, and also to accelerated wear and tear of stationary batteries. On the other side, connection of the ESS through dedicated converter interface to a regulated low voltage DC bus allows application of more flexible control and possibility of connecting multiple buses for enhancing the reliability of the system or to supply loads in a wider area. Moreover, the reliability of this system can be increased by using multiple battery stacks. This topology, operated at low voltage has by now been the most widely studied in literature [119]–[121]. However, its attractive features are partially counterbalanced with several associated technical problems. First, there now appears a need for careful design of circuit and control parameters due to a fact that equivalent capacitance of DC bus gets much smaller than in case of direct battery connection. Secondly, there exists only one DC bus, compelling the consumers to be powered from it.

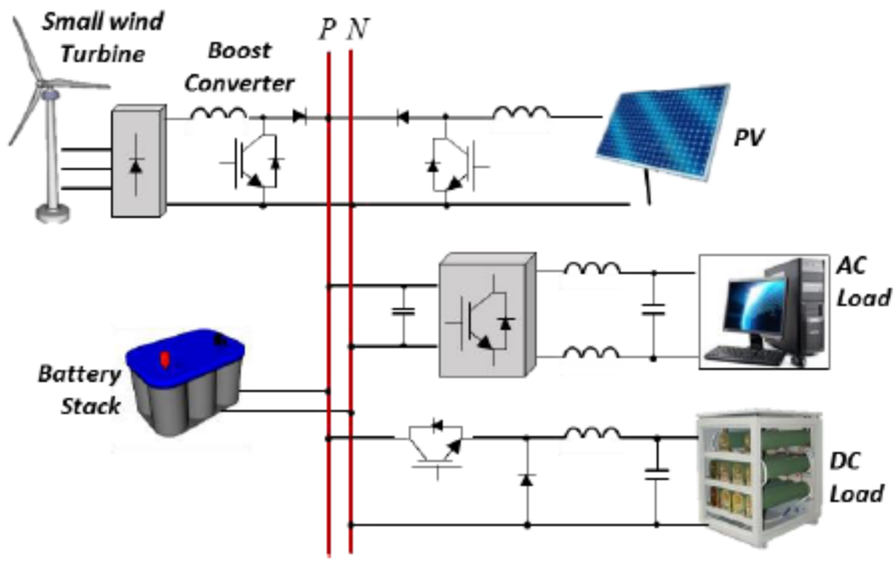

Figure 3.2. Single-bus DC microgrid

3.1.2 Multi-bus Topology. Besides the single-bus topologies, DC microgrids can be method of auctioneering diodes. In that particular work, the case of two redundant buses is analyzed. The location of intervention is on the load side where critical loads automatically select the bus to be supplied from based on higher voltage. The structure of this system is shown in Figure 3.3. Multiple DC microgrid cluster configuration, which is depicted in Figure 3.4, is an alternative redundant solution. In this way, every microgrid is able to absorb or inject power from its neighboring microgrids in case of shortage or surplus of power, respectively. Additionally, depending on the configuration in which the microgrids are connected, some corrupted buses can be automatically isolated from the system in case of failure. Power exchanges between multiple DC buses are regulated by imposing appropriate local voltage deviations. However, by dint of digital communication technologies, total average voltage can be regulated to a nominal value. Low voltage DC distribution systems can be interfaced to medium voltage AC utility mains through solid state transformer (SST). With connection of a number of SSTs to medium voltage AC network, it is envisioned that the energy extended to multi-bus configurations aiming at higher availability and reliability.

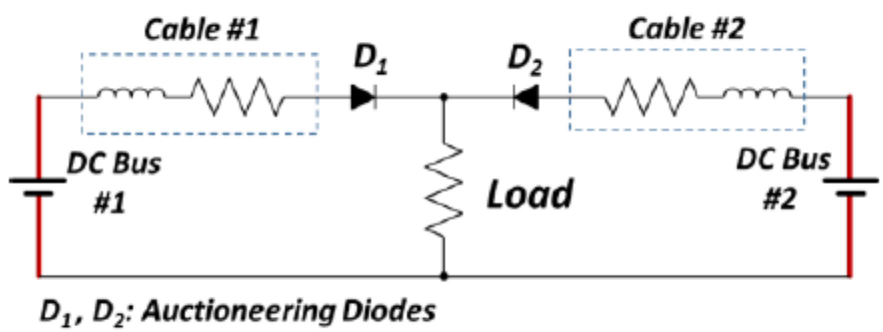

Figure 3.3. Dual-bus, separately fed DC microgrid with a bus selector at each load

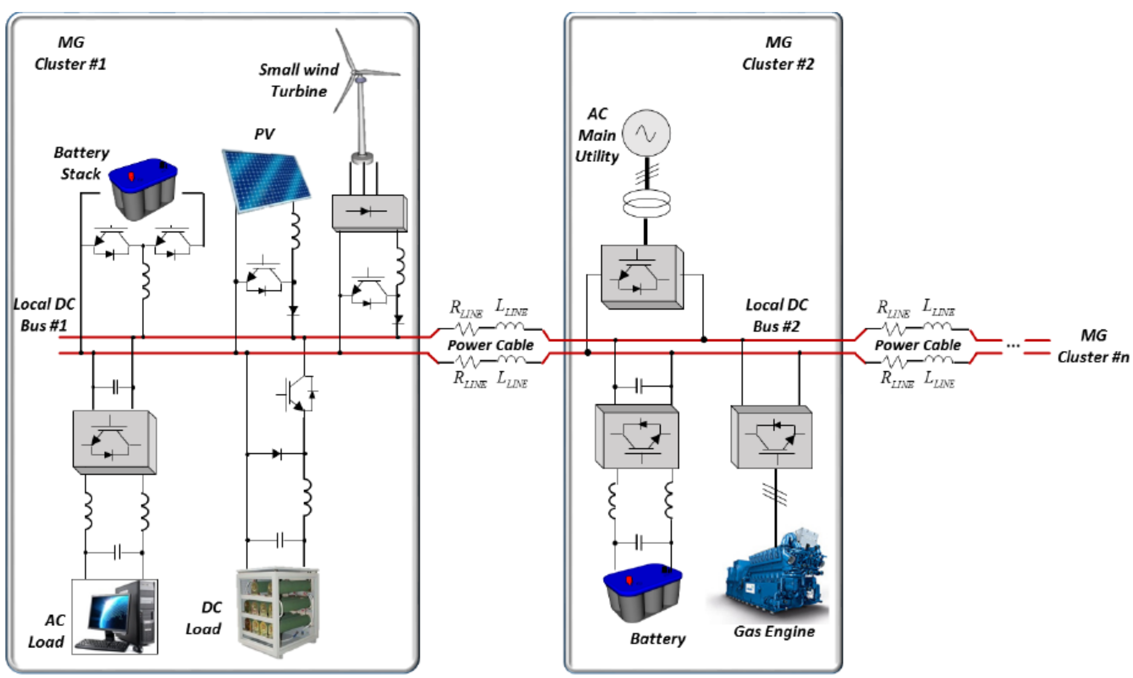

Figure 3.4. Multiple bus DC microgrid with all components through dedicated converter interfaces.

3.1.3 Reconfigurable Topology. Besides the aforementioned architectures of DC microgrids, reconfigurable topologies were also proposed for the purpose of increased flexibility during the faults or periodic equipment maintenance periods. Figure 3.5 shows DC ring bus architecture. Each node and the link between neighboring nodes are controlled by intelligent electronic devices (IEDs). The main merit of this configuration is high reliability and redundant operation. Since the load connected to the common DC bus can be fed bi-directionally, alternative path is provided at the ring bus in case of fault. When encountering a fault in this DC series to form a zonal architecture. Note that each DC distribution unit in the zonal configuration has two DC buses. These two buses form the redundant configuration and the required load power can be flexibly obtained by either one of them. In particular, assuming that the load power is supplied by the upper bus, in case of its failure the switches at the upper side are turned off and the switches at the lower side are turned on to change the source bus and ensure the normal operation of the load. Meanwhile, since each DC distribution unit in the zonal architecture is powered by the utility grid separately, fault can be isolated within each unit without influence on the operation of other parts of the zonal system.

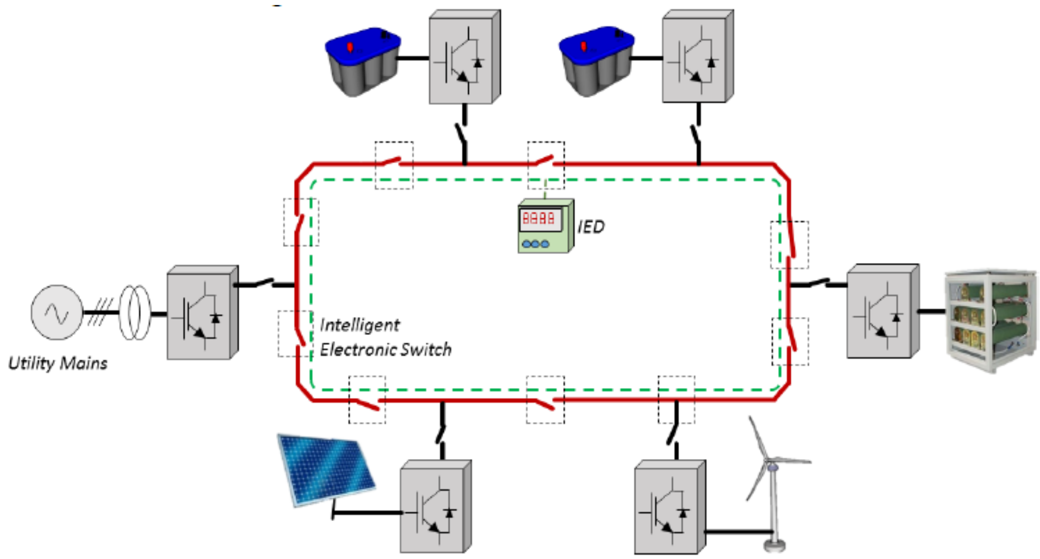

Figure 3.5. DC microgrid based on ring bus

3.2 Grounding and Protection Issues in DC Microgrid

As opposed to many advantages that DC systems bring in relation to AC, design of their protection represents a considerable challenge. The most important aggravating circumstance in that view is problem with extinguishment of DC arc, which inevitably appears upon the tripping of protective devices. On the other hand, as worldwide industry has just recently started to conceive DC microgrids as serious actors, there is still a general lack of understanding and experience with operational issues of these systems. Therefore, widely accepted protection standards and guidelines are yet to be defined.

3.2.1 Types of Faults. Figure 3.6 shows two basic types of faults that can exist in DC power systems, i.e., line to ground and line to line faults. It should be noted that although less serious, line to ground faults are the ones most frequently appearing in industrial distribution systems. Line to ground fault can have either low or high fault impedance, while line to line fault typically has a low impedance. Moreover, a fault can occur at various points in the system, and each one of them will have different implications. For instance, unlike feeder faults that can be rapidly isolated from the main bus, faults at the main bus itself present a greater danger since all the feeders connected to it get affected.

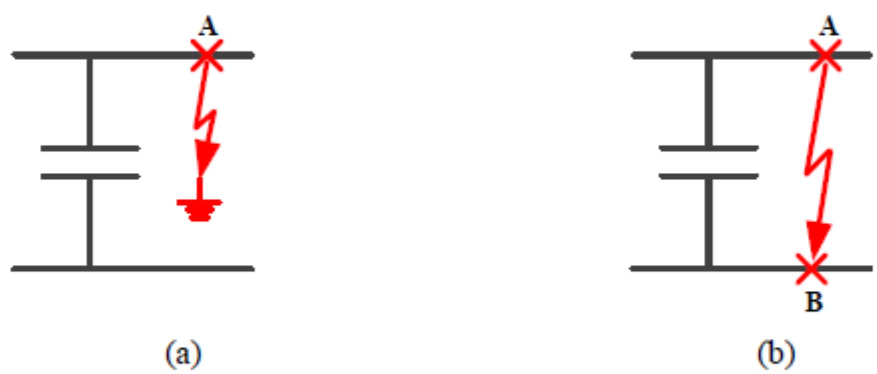

Figure 3.6. Two fault types in DC systems, (a) line to ground fault and (b) line to line fault

3.2.2 Grounding. Different grounding alternatives have been proposed for DC power systems. Some references suggest ungrounded operation, especially for low voltage applications. The reason for that is a fact that the common mode voltage will typically not be on such a high level to present a danger for personnel safety, and will offer a possibility of continuing operation even in case of a single phase-to-ground fault. Still, it is instrumental then to discover and correct a possible second ground fault or it will create a line-to-line fault. In grounded mode, either a solid, low or high resistance grounding can be applied. Solid grounding is rarely used in modern systems because of the pronounced stray current induced corrosion. There are a number of options regarding selection of the point in the system to be grounded; it can be either a positive pole, mid-point or negative pole of the common DC link [122].

3.2.3 Protective Devices. Protection devices that are presently commercially available for DC systems include fuses and circuit breakers (CBs). However, they inherently introduce large time constants and time delays before activation, respectively. In addition, interruption of the current in both cases is accompanied by the appearance of the arc. While arc gets extinguished naturally in AC systems within the half cycle after tripping by first crossing of the current through zero, it presents a challenge in DC systems since the current has a steady value. Arc occurrence presents a dangerous condition not only from safety point of view, but also causes contact erosion in CBs and consequently a short lifetime and high maintenance costs. Fuses operate on a principle of melting down the fuse link in a heat-absorbing material. Their ratings are specified in terms of RMS values of voltages and currents, and are hence equally applicable to AC and DC systems. However, it needs to be ensured that the time constant of current increase during the fault is below certain limits since slow increase of temperature may prevent the heat-absorbing material to extinguish the arc. Standard molded-case circuit breakers (MCCB) that consist of a contactor, a quenching chamber and a tripping device can be used as well. They can have either a thermal- magnetic or electronic tripping device. In either case, sufficient voltage blocking capability can be achieved by connecting contactors in series. One potential problem with MCCBs in systems dominated by power electronic converters, as is the typical.

3.3 DC Microgrids Costs

3.3.1 Capital Cost. Capital cost is broken down into two main categories, the cost of the power conversion electronics and other major equipment (e.g. switches) and the cost of the other materials needed to install the power systems. Rough estimates of the costs show that DC architectures perform better when integrating distributed energy sources that are DC-native (i.e. PV and Battery instead of synchronous machine-based firm generation) and when microgrid controls are used to manage the interface flows between the microgrid and the bulk AC system so that this interface can be made unidirectional (i.e. AC-DC import only) [123]. Both AC and DC microgrid systems will require a utility-grade disconnect switch and/or protection at the point of common coupling (PCC) to the main AC grid. However, both AC and DC microgrids will likely require a method for quickly disconnecting from the main AC grid for AC outages or other disturbances. For the DC microgrid, the power electronics interface will probably be sufficient, however, the AC microgrid will need an additional fast disconnect switch. If an electromechanical switch is used at the PCC, the cost will be insignificant compared to the power conversion equipment, however, the transient performance of the AC microgrid maybe impacted by the slower switching times.

3.3.2 Operation Cost. A microgrid can reduce its net operating costs in three ways: 1) improvements in energy efficiency reduces net energy imports, 2) the time of energy imports can be modified to reduce costs against a time-of-use tariff, demand charge, or other time-dependent energy billing, and 3) the microgrid collects revenue by supplying ancillary services to the AC grid. With respect to supplying ancillary services, there is no fundamental difference between an AC and DC architecture. In the DC architecture, the ancillary services are supplied from a single power electronics interface, but just like and AC architecture, providing these services requires coordination of multiple assets inside the microgrid. In the context of this idealized study of generic architectures, the two managed microgrid systems (whether AC or DC architectures) are using microgrid generation and storage to reduce power imports from the main AC grid to zero so that the microgrid's energy and demand charges are zero.

3.4 Control Systems

Although DC microgrids do not have a power system frequency, their control systems can be analyzed in a framework similar to AC microgrids and power systems. Specifically, the control is separated into two time scales—a fast time scale on the order of milliseconds to a few seconds or even a minute and a slower (~minutes) time scale. In analogy with AC power systems, we call control at the fast time scale "primary" and the slower time scale "secondary" slower time scale "secondary". The "secondary" controls generally use relatively slow communications to manage generator, storage, and load power for economic considerations and voltage set points for loss minimization. Other slow functions can also be managed at the secondary control time scale, e.g. (potentially adaptive) protection settings or device status. The implementation of the secondary control is not anticipated to be significantly different in the AC or DC architectures. In contrast, the primary control responds to fast microgrid transients or other upsets. The required speed of the primary response and critical nature of the control makes a communication-based control perhaps less reliable.

In DC architecture, voltage replaces frequency as the physical variable that can be used to communicate the imbalance of generation and load at the "primary" control time scale. As opposed to frequency in AC architectures, voltage in DC architectures is a "local" variable, i.e. the droop of voltage depends on the location of the change in load relative to the location of generation and the measurement point. When using voltage as the indicator of generation-load imbalance, the response of the generation or storage sources will not be uniform across DC microgrids. Although the configuration of the response at the primary time scale may not be desirable, but it can be adjusted at a slower time scale using the secondary control. However, at the faster primary time scale, the response is coming entirely from power electronic devices with more or less equivalent dynamics avoiding the complications of controlling mixed microgrids in AC architectures.

In order to guarantee stable and efficient operation of a DC microgrid, effective control strategies should be developed. In general, microgrid consists of a number of parallel converters that should work in harmony. Local control functions of these converters typically cover the following: (I) current, voltage and droop control for each unit; (II) source dependent functions, e.g. MPPT for photovoltaic (PV) modules and wind turbines, or a state-of-charge (SoC) estimation for energy storage systems (ESSs); (III) decentralized coordination functions such as local adaptive calculation of virtual resistances (VRs), distributed DC bus signaling (DBS) or power line signaling (PLS). At a global microgrid level, a digital communication-based coordinated control can be implemented to achieve advanced energy management functions. It can be realized either in a centralized or a distributed fashion, via central controller (CC) or sparse communication network, respectively. In case of distributed control, variables of interest are exchanged only between local controllers (LCs). Consensus algorithm can then be used to calculate either the average of all the variable values in distributed LCs or the exact value of any variable present in a specific LC.

Some of the functionalities that can be accomplished by using DCLs include secondary/tertiary control, real-time optimization, unit commitment, and internal operating mode changing. The basic configuration of each of these control structures is depicted in Figure 3.7.

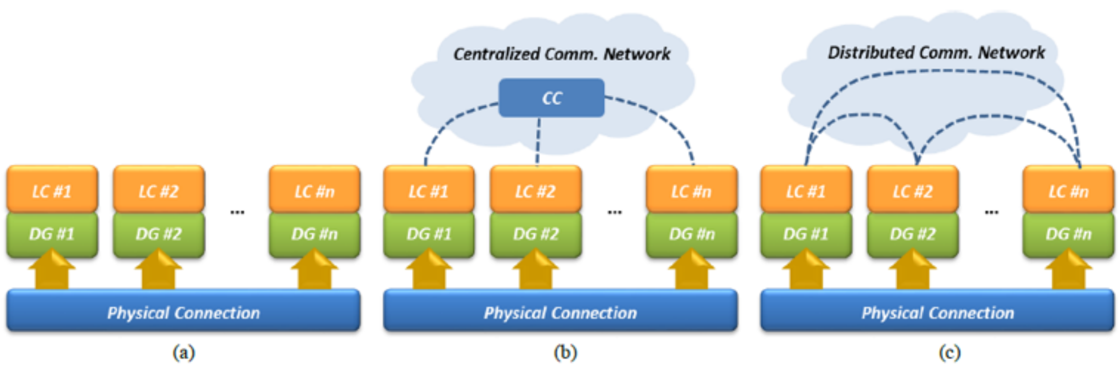

Figure 3.7. Operating principles of basic control strategies. (a) Decentralized control. (b) Centralized control. (c) Distributed control

3.4.1 Local Control in DC Microgrids. As previously mentioned, the control framework of a DC microgrid consists in general of local and coordinated control levels. In this section a local control level is discussed in detail. Basic functions, which include current, voltage and droop control, are reviewed. As a backbone of a DC microgrid, the interface converters play an important role in efficient and reliable operation of the overall system. In order to ensure not only proper local operation, but also to enable coordinated interconnection between different modules in a DC microgrid, flexible local current and voltage control should be employed and accurate power sharing among parallel connected converters should be achieved.

For local DC current and voltage control systems in DC microgrids, proportional-integral (PI) controllers are commonly used since they introduce zero steady-state error, can be easily tuned, and are highly robust. Proportional-derivative (PD) controllers can be used to improve the phase margin of the system, but they do not eliminate steady-state error and also need to have high frequency poles in order to attenuate high frequency noise. Hence, rather than appearing in a pure PD form, the derivative term in a PD controller is usually replaced by a high-pass digital filter. By combining the beneficial effects of PI and PD controllers, PID controllers can be employed. Fuzzy control is designed to emulate a human being's conclusion deduction process based on the stimulus he/she gets from the environment and his/her own embedded knowledge. In the engineering world, it can be defined as a knowledge-based control method that can simultaneously take advantage of both static and dynamic properties of the system. For the purpose of local voltage and current regulation fuzzy controllers can either be used as principal regulators that process the error signal or in a series with feedback loops. To ensure fast convergence and extreme robustness, nonlinear control strategies based on state-dependent switching can be employed. They present simple implementation, but their detailed performance analysis can be quite complex. It should be noted that alternative control methods for DC microgrids have recently drawn a lot of attention in the academic circles. However, their practical application should be elaborately justified by performing modeling, analysis, simulation, implementation as well as a full cost-benefit analysis. For instance, increased production cost and lead time often prove to be too large of an obstacle for their deployment.

3.4.2 Coordinated Control in DC Microgrids. Although the local interface converter control is an essential part of a DC microgrid, coordinated control should be implemented in order to achieve an intelligent control system with extended objectives. As already mentioned, depending on the means of communication between the interface converters, it can be realized either by using decentralized, centralized or distributed control.

3.4.2.1 Decentralized Control. Decentralized coordination strategies are achieved exclusively by LCs, as shown in Figure 3.7. In this section, we will review a number of decentralized methods that can coordinate the performance of multiple converters in DC microgrids. The most common ones are DC bus signaling (DBS), adaptive adjustment of droop coefficients and power line signaling (PLS). While there advantage is simplicity of control and independence from digital communication technology, they inherently have performance limitations due to lack of information from other units. Moreover, as these methods are invariably based on the interpretation of the voltage in the common DC bus, the accuracy of voltage sensors impacts their effectiveness and reliability. DBS is the most prominent decentralized coordination method for DC microgrids. By using the DBS approach, coordinated operation of different units in DC microgrids is realized by imposing and identifying variations in the common DC bus voltage. The DBS principle is shown in Figure 3.8, where three operating modes are developed and each one of them includes a different combination of operating statuses for PVs, ESSs and AC grid interfacing converters. It can be seen from the figure that units are represented either as current sources/sinks or by Thevenin equivalent circuits, depending on their internal operating mode. The Thevenin circuit actually demonstrates that a given unit is in the droop control mode. The voltage source then corresponds to a voltage reference, while the series impedance corresponds to virtual impedance. The transitions between different modes are triggered by different preset DC bus voltage values.

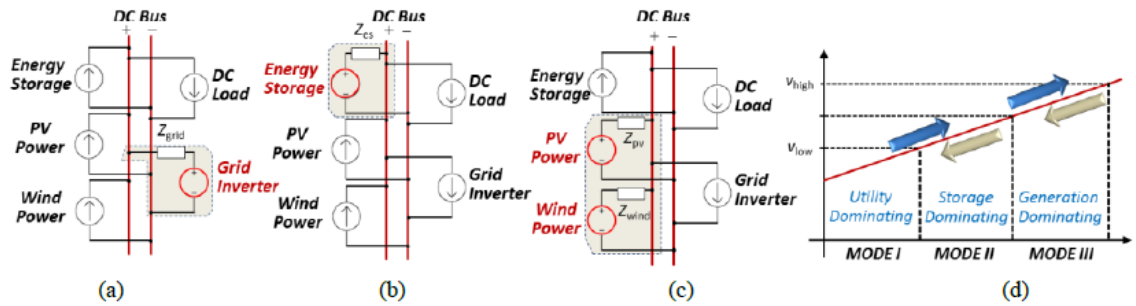

Figure 3.8. Operation modes and basic principle of the DBS approach. (a) Utility dominating mode. (b) Storage dominating mode. (c) Generation dominating mode. (d) Basic principle of the DBS approach

DBS relies only on local information and does not need any other components other than interface converters. Therefore, it is a decentralized control method that is easy to implement. The main concern here is the selection of appropriate voltage levels which are needed to identify different operation modes (as shown in Figure 3.8). If the difference among the adjacent voltage levels is too large, the DC bus voltage fluctuation will exceed the acceptable range. Still, the difference among the voltage levels should not be too small since sensor inaccuracy and the DC bus voltage ripples could then prevent reliable identification of proper operating modes.

Adaptive calculation of droop coefficients is an extension of conventional droop control, which does not consider change of operating modes. It is commonly used to balance SoC among multiple ESSs in order to avoid their overcharge or over discharge. The method of adaptive droop coefficient calculation has been mainly used for power balancing of distributed ESSs. The main limitation of the method is potential instability induced by improperly designed droop curves. To that end, there always exists a tradeoff between the permissible voltage deviation and stability properties of the system, i.e. higher voltage deviation is associated with the higher phase margin.

PLS is another decentralized method that can be deployed for coordinated control. In particular, sinusoidal signals of specific frequency are injected through amplifiers into the DC bus, allowing each device to send and receive information on its status, performance, history or internal operational mode. Although PLS relies on digital communication, here it is categorized as decentralized since the power network is the only communication medium. It should be noted that in power systems literature, this particular way of communication is sometimes also referred to as power line communication (PLC). In general, PLS is complex to implement in DC microgrids.

3.4.2.2 Centralized Control. Centralized control can be implemented in DC microgrids by employing a central controller and a digital communication network to connect it with sources and loads. For small scale DC microgrids, each unit can be directly controlled by the central controller that employs a high bandwidth communication using a master/slave approach. However, for larger scale DC microgrids, hierarchical control is often a preferred choice since it introduces a certain degree of independence between different control levels. It is more reliable as it continues to be operational even in case of failure of centralized control. Hierarchical control is achieved by simultaneously using local converter control and DCL-based coordinated control, which are separated by at least an order of magnitude in control bandwidth. Coordinated functions can include secondary/tertiary regulation of DC voltage, power flow control and different gridinteractive control objectives such as unit commitment, changing operating modes, global optimization aimed at maximizing efficiency, minimizing operating cost etc.

It should be noted that centralized control provides the best foundation for employment of advanced control functionalities since all relevant data can be collected and processed in a single controller. However, the most obvious disadvantage of this strategy is that it has a single point of failure. In particular, if the central controller or any key communication link fails, the commands from/to the controller will not be transmitted and corresponding control objectives will likely not be achieved. For mission critical applications, redundant communication systems can be installed in order to reduce the possibility of failure, but this needs to be justified by a cost-benefit analysis. Another option to increase the reliability of the system is to combine decentralized and centralized control methods into a hierarchical control structure. In that case, basic functions of DC microgrids can be retained even if the centralized controller fails.

3.4.2.3 Distributed Control. Distributed control indicates the control principle where central control unit does not exist and LCs communicate only among themselves through dedicated DCLs. The main advantage of this approach is that the system can maintain full functionality, even if the failure of some communication links occurs, provided that communication network remains connected. Therefore, distributed control is immune to single point of failure. The functionalities that can be achieved by this approach resemble those of centralized control. However, in order to enable these functionalities, the information exchanged through DCLs first needs to be appropriately processed. In particular, information directly exchanged between LCs can contain only locally available variables. In other words, if the two units are not connected by a DCL, they do not have direct access to each other's data and their observation of the system is quite limited. In order to circumvent this problem and to make the level of awareness of an LC similar to that of a CC, a consensus algorithm can be used. In its basic form, a consensus algorithm is a simple protocol installed within every LC which continuously adds up all algebraic differences of some variable(s) of interest present in a given LC and those present in LCs adjacent to it.

Distributed control can achieve information awareness comparable to that of centralized control. Therefore, objectives such as output current sharing, voltage restoration, global efficiency enhancement; SoC balancing and others can be easily realized. In that sense, distributed control offers much wider functionalities than decentralized control, but remains protected from the single point of failure. Its main limitation is complexity of analytical performance analysis, i.e. assessment of convergence speed and stability margins, especially in non-ideal environments characterized by communication time delays and measurement errors.

3.5 Communications

From the communication perspective, overall control of DC microgrids can be divided into the following three categories:

- Decentralized control: DCLs do not exist and power lines are used as the only channel of communication.
- Centralized control: Data from distributed units are collected in a centralized aggregator, processed and feedback commands are sent back to them via DCLs.

• Distributed control: DCLs exist, but are implemented between units and coordinated control strategies are processed locally.

Power Over Ethernet (PoE), Universal Serial Bus (USB), and Power Over HD Type-T (PoH) have all combined communications with the distribution of DC power on the same set of wires at voltages up to 55 V DC and powers up to 100 W. The use of the same wires is perhaps not that advantageous—an additional set of wires could be added to AC wiring to enable communications in a similar fashion. However, the logical connection between the wires that are carrying the power and the power consuming device enables a mode of device discovery and power and voltage level negotiation. This functionality could enable an automatically reconfigurable DC microgrid that approaches the plug-and-play capability of today's computers. The implementation of these concepts in DC architectures is not straightforward. Today's power management capabilities of PoE, USB and PoH rely on a hub-and-spoke network architecture with a single device at the end of each spoke. Such an architecture may not be limiting for the low-voltage (24-48 V DC) loads where cable lengths are limited by Ohmic losses. However, the high voltage networks will certainly incorporate many devices on a single run of cable. The communication protocols used in PoE, USB, and PoH are not applicable in this architecture. Plug-and-play DC architectures would require the development of new protocols that enable device identification and packet routing in this more complex network architecture.

CHAPTER 4

HYBRID MICROGRID

Microgrids have been widely studied in the literature as a possible approach for the integration of distributed energy sources with energy storage systems in the electric network. Until now the most used configuration has been the AC microgrid, but DC-based microgrids are gaining interest due to the advantages they provide over their counterpart (no reactive power, no synchronization, increasing number of DC devices, etc.). Therefore, hybrid AC/DC microgrids are raising as an optimal approach as they combine the main advantages of AC and DC microgrids.

There are various advantages relating to hybrid AC/DC microgrids. For instance, both AC and DC-based devices may be directly connected to the network with limited interface elements. As a result, the energy losses are reduced due to reduced number of conversion stages. This feature makes hybrid microgrids suitable for the integration of the increasing DC-based units such as electric vehicles (EVs), photovoltaic (PV) systems, fuel cells, laptops, and mobile phones. Another advantage is that there is no need for synchronization of generation and storage units as they are directly connected to the AC or the DC network. Thus, simplified control strategies need to be developed. Moreover, the transformation of voltage levels is also simplified. In the case of AC, transformers may be used and in the DC case DC-DC converters.

On the other hand, there are some disadvantages related to the use of hybrid AC/DC microgrids. Protection schemes designed for DC systems have not been thoroughly developed compared to the variety of protection systems and devices that are found in AC systems. In addition, fault detection in AC systems is simpler due to the zero-crossing of the current. In terms of reliability, the reliability of AC microgrids is higher compared to hybrid AC/DC microgrids. The reason is that an interface power converter is introduced in the distribution network to introduce the DC-link. However, the reliability of the connected devices is improved as the number of converter stages is reduced. Finally, the energy management of hybrid microgrids is more complex and in its counterparts, i.e., AC or DC microgrids. This is due to the fact that control systems need to be implemented for the AC and DC networks as well as the interface power converter between them.

4.1 System Layout

There are several available system layouts, which are distinguished by the way the microgrid is connected to the utility grid and the structure of the inner current conversion stages. In Figure 4.1, two main groups can be identified for the interface devices placed between the AC, DC and the utility that is coupled AC and decoupled AC configurations.

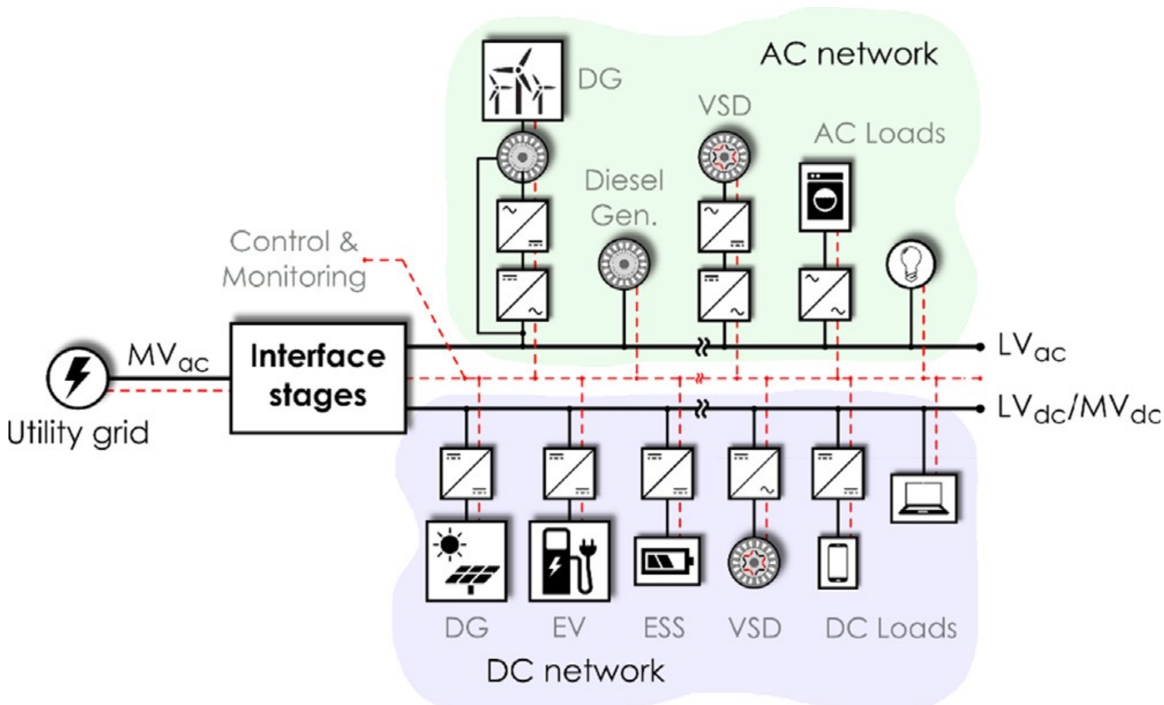

Figure 4.1. Example of a Hybrid microgrid configuration

At coupled AC topologies the AC network of the microgrid is directly connected to the power grid by a transformer and an AC-DC converter is used for the DC network. Alternatively, decoupled AC configurations are composed at least by an AC-DC and DC-AC stage; this means there is no direct connection between the power grid and the AC network of the microgrid.

4.1.1 Coupled AC Microgrids. The main feature of this configuration is that the AC network is directly connected to the power grid by a transformer. The advantage is that the AC network of the microgrid is fixed by the utility grid in normal operating mode. In addition, the development of a coupled AC microgrid is less expensive than the decoupled one. This is due to the smaller size of AC-DC converter that is needed to handle the power flow between the utility grid and the dc network. Two principal methods have been found for the arrangement of conversion stages in coupled AC microgrids. In the first case, as it can be seen in Figure 4.2, a transformer is located at the point of connection with the power network. This reduces the voltage level so that low voltage AC and DC networks are generated.

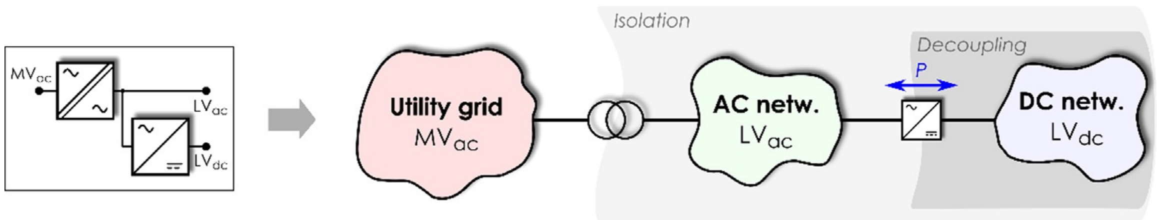

Figure 4.2. Coupled AC, completely isolated hybrid microgrid configuration

Another configuration is depicted Figure 4.3, where the AC-DC converter that generates the DC microgrid is directly connected to the utility grid, instead of being after the power transformer. Consequently, the rated power of the transformer is lower than in the previous approach, as it has to handle the power flow of the AC network. However, this means there is no galvanic isolation for the DC network of the microgrid, unless a second transformer is integrated.

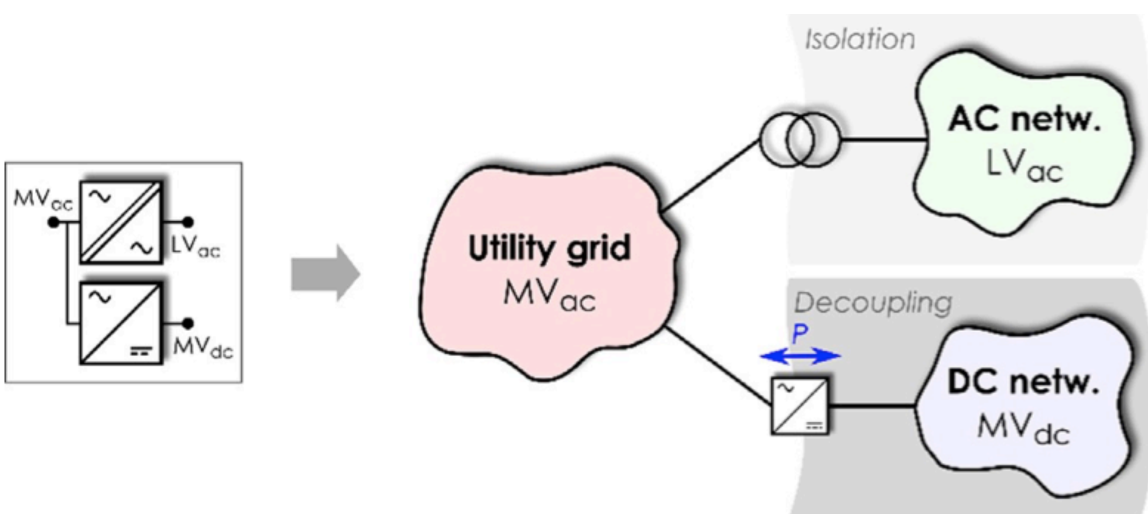

Figure 4.3. Coupled AC, partially isolated hybrid microgrid configuration

In the case of coupled AC hybrid microgrids with entire isolation (Figure 4.2) the authors in [124] propose a hierarchically configured microgrid with both AC and DC links. The architecture is divided in three main levels: micro-source level, where the dc-link, distributed generation (DG) and energy storage systems (ESS) are located; combo-source level, where the AC-link and the inverter for the connection between links is placed, and the microgrid level, where the interconnections of the lower level facilities and the power network are performed. According to the authors in [124], this architecture improves the flexibility and reliability of the distribution network over conventional configurations. Although this topology is suitable for the integration of DG units in the power grid, not all the capabilities of hybrid microgrids are used—i.e. the number of interface converters is not optimized as AC-based DG units are connected to the DC-link instead of the AC-link. A more efficient approach would be to directly connect these generation units to the AC-link of the network. A similar approach where a hybrid microgrid capable of managing the power flow in two directions (consumption/generation) by the utilization of a bi-directional AC-DC converter is proposed in [125].

4.1.2 Decoupled AC Microgrids. This type of configuration is gaining interest due to the advantages it provides over coupled ones. Firstly, the AC network of the microgrid is decoupled from the utility grid by a DC stage, which provides fault isolation and independent control strategies for both sides of the microgrid. Moreover, the power flow monitoring and control of the microgrid is inherent of the interface device, which is useful for the coordination with upper level control platforms such as the supervisory control and data acquisition (SCADA) systems.

In order to develop the configurations under this category, the integration of solid state transformers (SST) is envisioned as one of the most promising alternatives [126]-[130]. The key feature of these devices is that they can directly replace the current passive transformers while enabling management over the power flow. Moreover, they ensure decoupling between the power grid and power network, and provide a DC-link that is necessary for the development of a hybrid microgrid. These devices are suitable mainly for traction and distribution grid applications.

SSTs are composed by staged power transformers and can be arranged in numerous configurations. However, three architectures that cover the most important SST topologies have been identified in the studies carried out in [127][129][130]: two-stage SST with low voltage (LV) DC network, two-stage SST with medium voltage (MV) DC network and three stage SST network with LV and MV DC networks (Figure 4.4). The differences between the three configurations reside in the location of the transformer and the stages of the converter. In the first approach, the transformer is located at the input of the SST, providing galvanic isolation to the entire microgrid. However, in the second configuration, this transformer is placed at the LV AC network, which ensures isolation for this grid uniquely. Finally, in the third approach, a DC-DC stage is introduced where a high frequency (HF) transformer is installed. This provides isolation for the LV AC and DC networks, while enabling a MV DC-link.

Regarding the first approach, several studies can be found in the literature [127][131–136]. In [131], a solution for the integration of DG units by the use of an energy conversion station is proposed. According to the authors, this approach avoids the problems that appear when integrating DG units in the conventional AC grid—e.g. stability or synchronization issues. Moreover, it supposes no additional cost for conventional grid consumers in microgrids. A similar approach is studied in [132], where the integration of DG and ESS systems is performed by a back-to-back converter with a middle DC-link. The solution is validated and it is concluded that the system operates reliably with various DG units.

Another solution related to the second configuration shown in Figure 4.4 is presented in [137]. In this approach, an AC-DC stage is introduced to provide the DC network, and afterwards a DC-AC converter is included with a high frequency transformer for isolation and a cycloconverter that determines the output voltage sign. Although the voltage levels in this solution are all of LV, the same approach could be developed for MV to LV conversions, as has been studied in [138].

Even if two-stage solutions are the simplest approach for the generation of the DC network in terms of conversion stages, the three-stage topology is one of the most studied approaches in the literature due to the advantages it presents [126–128][134][135]. Among other features, this architecture provides MV and LV DC networks in addition to the LV AC one. Moreover, even if this topology employs a MV DC stage as in the second solution, the use of a medium frequency (MF) transformer in the DC-DC stage provides galvanic isolation of the LV-side of the microgrid and drastically reduces the size of the device. These features make this configuration suitable for the integration of small- or high-scale DG, ESS or loads even if galvanic isolation is not provided for the MV DC network.

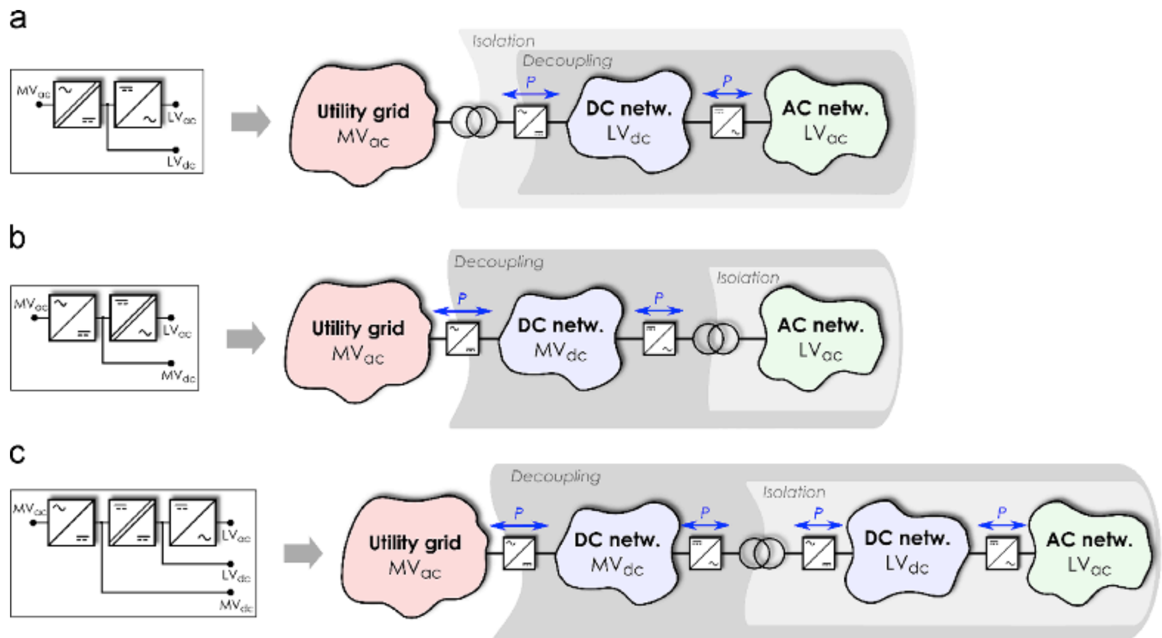

Figure 4.4: Hybrid microgrid with decoupled AC network: (a) two-stage completely isolated configuration, (b) two-stage partially isolated configuration and (c) three-stage

4.1.3 Summary. Table 4.1 collects the features of the hybrid microgrid architectures in terms of the aforementioned characteristics. The comparison shows that the maintenance and cost are higher for the decoupled AC topologies and their reliability is not as good as the transformer-based alternatives. However, their scalability and modularity are higher and the volume of the devices is lower in most of the cases. This makes them suitable for the development of hybrid microgrids as they provide high upgrading capabilities—which is necessary for the upcoming DG and ESS systems—as well as power flow management and isolation. Moreover, these topologies can actively perform the fault management for the entire microgrid.

Table 4.1. Comparative evaluation of hybrid microgrid configurations

Feature	Coupled AC		Decoupled AC		
	Completely isolated	Partially isolated	Two-stage completely isolated	Two-stage partially isolated	Three-stage partially isolated
Galvanic isolation	Complete	AC network	Complete	AC network	AC & LV DC networks (not the MV DC network)
Volume	High	Medium	High	Medium	Low
Cost	Low	Medium	Medium	High	High
Maintenance	Low	Low	Medium	Medium	High
Reliability	High	High	Medium	Medium	Medium
Scalability	Low	Low	High	High	High
Modularity	Low	Low	High	High	High
Controllability	Medium	Medium	High	High	High
Fault	Medium	Medium	High	High	High

4.2 Planning

The investment cost is typically higher for distributed energy resources (DERs) compared to conventional energy resources within large-scale power plants due to economies-of-scale of the latter. Nevertheless, DERs could provide less expensive energy in comparison with the energy purchased from the main grid specifically during peak hours when the market price is high. The energy storage could be further employed to be charged by the power from the main grid during low-price hours and discharged during high-price hours. One important and salient feature of microgrids that increases the reliability is their islanding capability, which allows microgrids to be disconnected from the main grid in the presence of faults, disturbances, or voltage fluctuations in the upstream network. However, if after disconnecting from the main grid, the microgrid could not supply all the loads, some loads should be curtailed, but critical loads will still be supplied. Another economic benefit of the microgrid is selling back the excess power to the main grid. The microgrid economic viability is ensured when the total microgrid revenue from all available value streams in a specified time horizon exceeds the microgrid total investment cost. The total planning cost is comprised of three parts: the investment cost, the operation cost, and the reliability cost. The investment cost is long-term, and is calculated annually while the operation and reliability costs are short-term, and should be calculated hourly for each day of the planning horizon.

A hybrid AC/DC microgrid can be developed by the addition of a power converter to the current distribution grid and the communication network for the connected devices. This makes the overall cost higher than AC microgrids because of the main power converter. However, if the number of attached devices increases, the investment will be returned faster as the number of total interface converters is reduced. Dual active bridge based converters have been identified as a feasible solution for the implementation of SSTs at hybrid microgrids, but the design of the medium frequency transformer of this converter is also an interesting approach that is already being studied and will continue developing in the near future. In addition, hybrid AC/DC microgrids are scalable and therefore their implementation can be performed at various levels and in several configurations. Their integration could be performed on a MV distribution network or on a LV residential environment.

4.3 Operation and Control

The classification of the most relevant hierarchical control level strategies can be observed in Figure 4.5 This classification has been performed based on the studies found in the literature, and their characteristics are explained in more detail in the following sections.

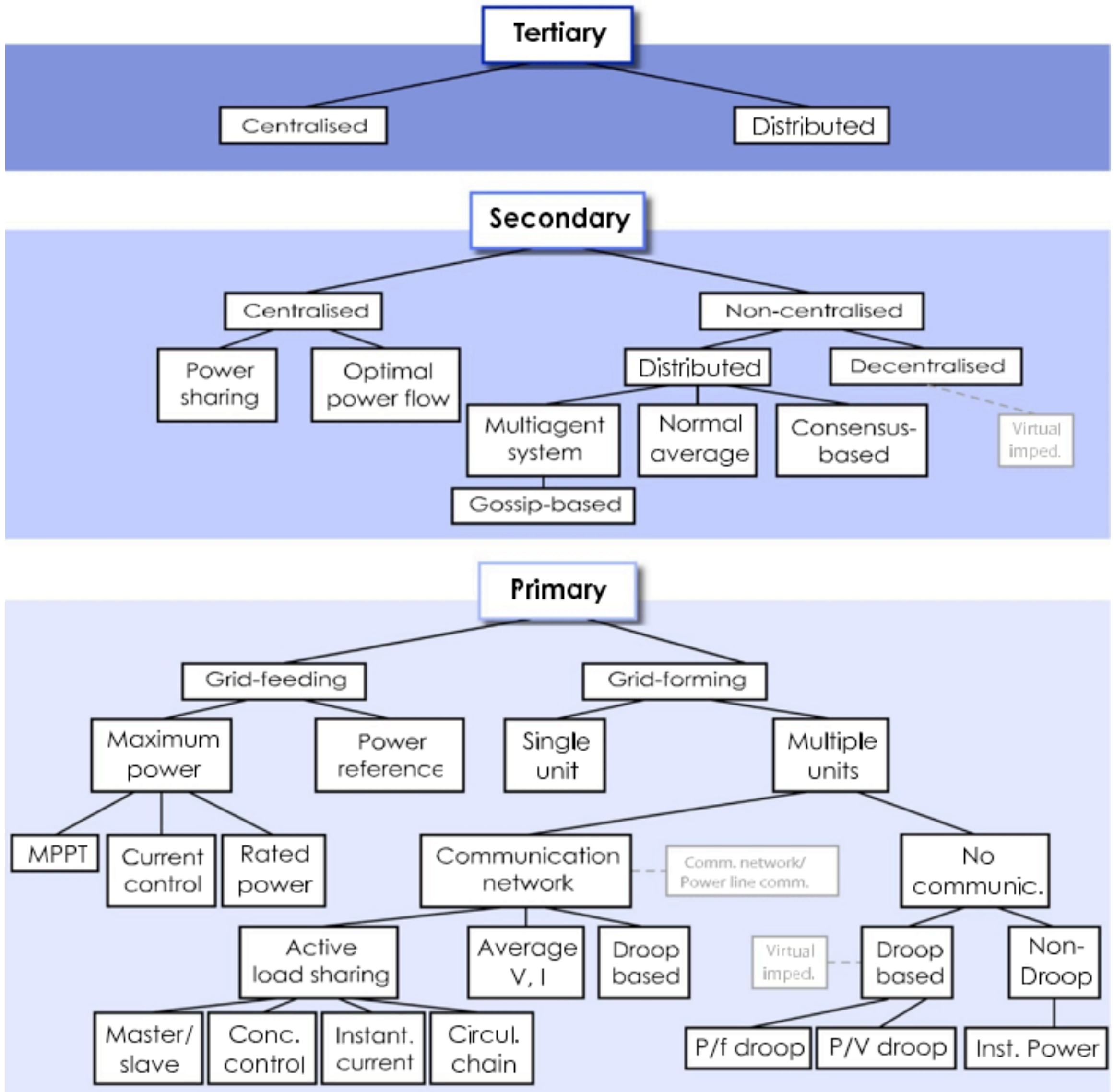

Figure 4.5. Classification table of the microgrid control strategies identified in the literature

4.3.1 Primary Control. The purpose of the local controller is to perform the current and voltage control of the interface devices connected to DG and ESS units. Optimal power management of resources and power sharing has to be ensured while providing voltage and frequency stability. In addition, lower-level protection is performed at this stage—e.g. inhibition of converters, contactors, etc.

In the literature usually two or three types of primary control levels are distinguished, depending on their function. Some authors state that three strategies can be implemented, namely grid-forming, grid-feeding/following and grid-supporting ones [139][140]. However, this classification could be simplified by reducing the number of primary control strategies to grid-forming and grid- feeding ones as described in [141]. The grid-supporting strategies are introduced in the grid-forming group because they contribute to the regulation of the grid voltage.

4.3.1.1 Grid-following Control. When operating in grid-tied mode, the voltage and frequency of the microgrid are established by the utility grid, so the local controllers of renewable energy sources (RES) usually operate in current-control mode to extract as much power as possible from energy resources—e.g. maximum power point tracking (MPPT) mode in wind turbine or photovoltaic systems, rated power operation in diesel/biomass generators, etc. Apart from that, this type of control can work in a non-optimal point—out of the maximum power range—when upper control levels set the references. Usually the purpose of this approach is to optimize the power sharing strategy of the network [140]. These strategies are equally implemented in AC- and DC-based units; the main difference is the synchronization process of the AC-based ones to the AC side of the microgrid.

4.3.1.2 Grid-forming Control. When an intentional or non-intentional islanding occurs, voltage and frequency stability of the AC and DC networks of the microgrid has to be ensured by DG and ESS systems. Therefore, an optimal active and reactive power control has to be performed so as to provide adequate power sharing between devices.

Depending on the requirements, some or all the DG units will operate to control the network voltage—i.e. in grid-forming mode—while the rest continue in grid-following mode. Two configurations have been identified for this control strategy [142]:

- Single grid-forming unit: one of the interface converters connected to DG units is in grid-forming mode and its reference is established to supply a certain voltage and frequency. The rest of the devices connected to this network are controlled to absorb as much power as possible from energy resources—i.e. in grid-following mode.
- Multiple grid-forming units: in this strategy, more than one interface converter is controlled in grid-forming mode. Consequently, a synchronization process is required to ensure voltage and frequency stability for both the AC and DC microgrid networks while performing a balanced power sharing.

4.3.2 Secondary Control. The main purpose of this control level is to compensate the voltage and frequency deviations in the networks that compose the microgrid (in the DC side of microgrids only the voltage). After a change in the load or generation of the microgrid, the secondary control regulates the difference between the established voltage/frequency references and the measured ones towards zero [143].

When operating in islanded mode, the secondary control strategy is the higher hierarchical control level, so it must ensure other features such as black-start management and resynchronization on the transition from islanding to grid-tied mode of operation.

Secondary control strategies are primarily categorized as centralized or non-centralized [143]. Depending on the architecture and the state of the microgrid, the control levels adopt different grades of responsibility.

4.3.2.1 Centralized Management. In centralized approaches, the management of the microgrid is performed from a central controller located at the global control level, usually named as microgrid master controller or MMC, as depicted in Figure 4.6. In order to do so, variables such as active and reactive power are collected from DG, ESS and critical loads; moreover, market conditions, security issues and requests coming from upper control units (e.g. the SCADA of the utility grid) are taken into account [143].

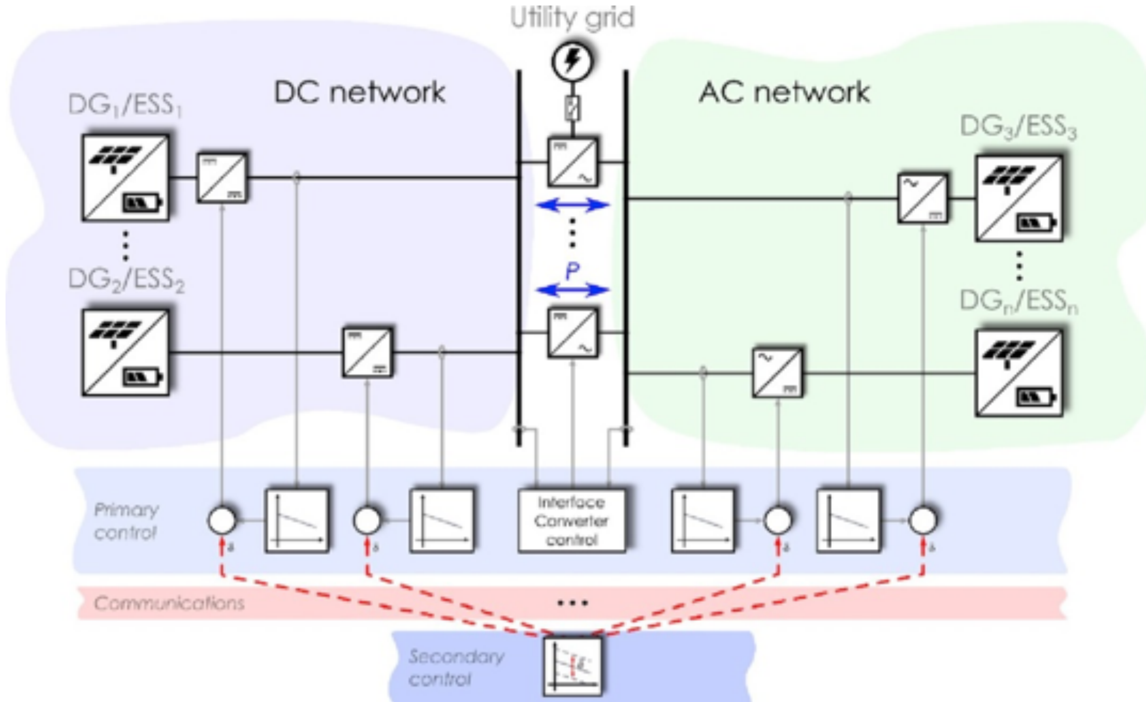

Figure 4.6. Concept of the centralized secondary control

4.3.2.2 Non-Centralized Management. In non-centralized control strategies, power management responsibilities recall in the generation and storage devices. This means that instead of being implemented in the MMC, they are integrated in the local controller, avoiding the communication network with upper level control strategies (tertiary and so on). The main advantage of these management strategies is that in case a fault occurs, the rest of the microgrid can operate normally after disconnecting the faulty unit.

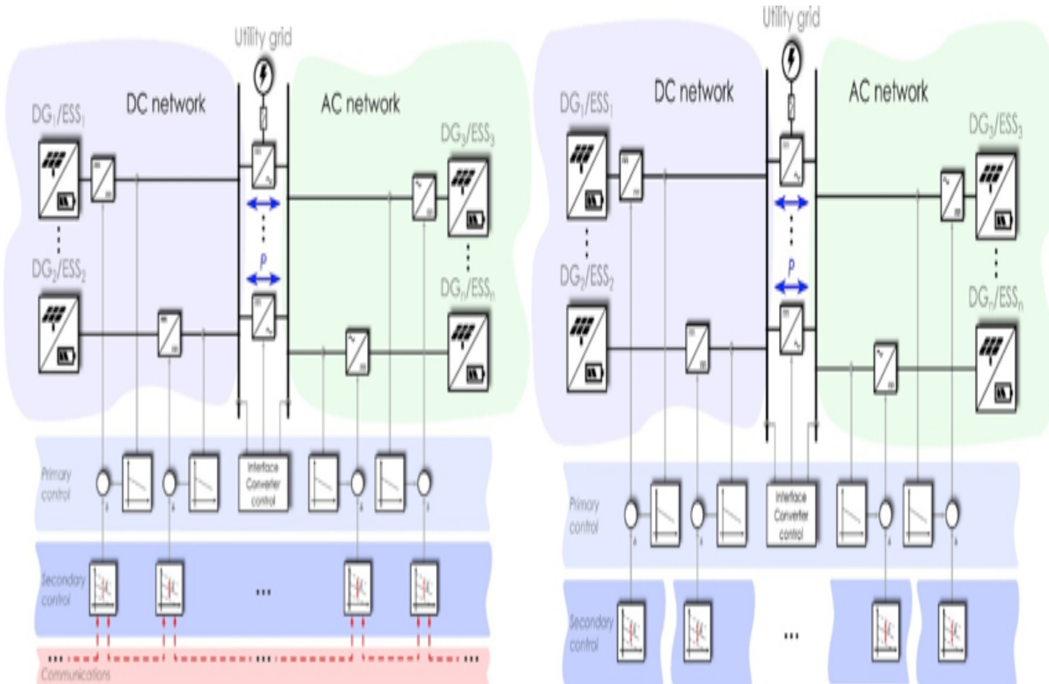

Figure 4.7. Concepts of non-centralized secondary control

4.3.3 Tertiary Control. When operating in grid-tied mode, the tertiary or global control level manages the active and reactive power flow between the microgrid and the utility grid by regulating the voltage and frequency of the microgrid. Similar to the secondary control level, this can be performed in two ways: as a centralized strategy where the tertiary control level is located at the MMC (which can be the SCADA system), or as a distributed technique where the entire control is located at the local controllers.

4.3.3.1 Centralized Management. In centralized techniques, power values are measured at the point of common coupling and they are compared to the desired values. P/Q reference values are obtained based on the power requirements of the microgrid and the market situation—i.e. energy cost, generation, storage and/or load forecasting, etc. This way, different variables can be optimized such as efficiency, economical benefit, control simplicity, power quality, etc.

4.3.3.2 Distributed Management. Usually, the tertiary control level is not located at the microgrid itself, but in the MMC of the main grid (e.g. at the SCADA). However, there exist some approaches where the tertiary control level is placed in the microgrid in a distributed manner.

4.4 Communications

There is a need for a communication network in order to implement the control strategies and therefore operate the hybrid AC/DC microgrid.

4.4.1 Primary Control Communication Network. The primary control strategies are usually based on active load sharing. They include master/slave, central or concentrated control, instantaneous current sharing or circular chain approaches, among others. The main disadvantage of these techniques is that the communication network can become extremely complex in highly extended microgrids, and it can cause failures in the control strategy if any part of the communication network has a fault. Moreover, plug and play capability is not ensured and makes the integration of upcoming devices a challenging task.

For a two-layer control strategy based on the droop control technique—which is a proportional control— for voltage- and current-controlled voltage-source inverters a device requires its own information and the information of the neighboring systems, but it does not make use of a central controller for the management of the microgrid.

Other solutions can be found where communication between DG and ESS devices is necessary but no communication network is present. These approaches are based on the communication between the power lines of the microgrid, which is also known as power line communication (PLC) or power line signaling (PLS). For example, signals of different frequencies may be sent through the power line so as to synchronize the converters connected to the grid. Although this strategy does not require any additional communication network, the control signals that circulate through the microgrid distort the voltage and frequency of the networks. Moreover, the integration of new generation or storage units in the microgrid is more complex as the range of frequencies where the signals can be injected is reduced when the number of devices already connected is high. Even if primary control strategies based on a communication network provide adequate power sharing and stability for the microgrid, they are not very used in the literature. A more usual approach is to employ an autonomous primary control with a centralized or distributed secondary control.

Droop control is one of the most studied strategies where no communication between devices is necessary. This control scheme presents several advantages over other control alternatives, such as: plug and play capability, power sharing, less faults due to the lack of a communication network, simple implementation, etc. The purpose of droop control is to vary the voltage amplitude and frequency references depending on the active and reactive power demand to perform the power sharing between devices. This strategy is widely used for the power sharing of synchronous generators in the conventional utility grid. In microgrids, ESS units often include this strategy to perform optimal current sharing when operating both in islanded or grid-tied mode.

Apart from droop-based techniques, other strategies can be found where no communication network is required. In [145], for example, the authors propose an alternative that is based on the instantaneous power theory. They imply that power sharing between devices can be achieved without any communication, barely with local measurements.

4.4.2 Secondary Control Communication Network. In a centralized hierarchical secondary control system the communication network links all the hierarchical control levels. Therefore, centralized control strategies become extremely difficult when a high amount of devices are connected at dispersed locations. However, they are suitable for the management of small-scale microgrid where there is a single or reduced number of DG and ESS owners, as they provide high plug-and-play capabilities.

The non-centralized control approach is envisioned as an attractive solution towards the integration of microgrids at the power distribution level, as it offers a more simple communication network while providing plug-and-play connection of devices. Two main variants can be found; one where a communication network is integrated, also named distributed control, and another where there is no communication between units (DG, ESS, etc.), also known as decentralized control. For distributed control, consensus or agent-based techniques may be used. Multi-agent systems (MAS) are one of the solutions for the distributed management of microgrids. In this approach, each local controller acts as an agent, making decisions over the parameters of the DG or ESS unit that is controlling. As it is a distributed strategy, the communication is performed only between neighboring devices.

Apart from MAS-based techniques, other distributed strategies have been also identified in the literature. These strategies are divided into three main groups: normal averaging, gossip-based (a type of MAS technique) and consensus based techniques.

For decentralized secondary control, several authors imply that decentralized control strategies are more suitable for microgrid systems as they need no communication and therefore plug and play connection of upcoming units can be ensured. Control techniques, which are for instance based on fuzzy inference, can provide voltage support.

The authors in [146] have performed a comparison between distributed and decentralized secondary control strategies, and state that even if it is possible to perform the management of the microgrid without any type of communication between devices, the distributed approach provides a better performance and reliability.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

DC microgrids hold great promise for ordinary residential and commercial buildings, where they could service the many electrical loads that use DC power. These include LED lighting and, increasingly, charging stations for electric vehicles, whose hefty batteries demand (or produce) DC. Heating, ventilation, and air-conditioning (HVAC) equipment and various household appliances are also well suited to powering with DC. That's because the most energy-efficient types of HVAC equipment and appliances incorporate variable-speed motor drives, for which AC power from the regional grid must be converted to DC internally. So it would be straightforward—and more efficient—to power such motors directly from a local DC source.

Including different types of microgrids, i.e., AC, DC and hybrid, general research has been accompanied in the operation and control of AC microgrids. DC microgrids could however offer several advantages compared to AC microgrids: providing a more efficiently supply of DC loads and reducing losses due to the reduction of multiple converters used for DC loads, easier integration of DC DERs, and eliminating the need for synchronizing generators. In this thesis, different components of AC and DC microgrids were illuminated, followed by developing a microgrid planning model with the objective of determining the optimal DER generation mix and the type of the microgrid, i.e., either AC or DC. It was shown that the DC microgrid is more economically viable solution than the AC microgrid. In other words, for small ratio, AC microgrid would be more economical and for larger ratio, DC microgrid would be more economical.

Microgrids are envisioned as an attractive solution towards the integration of DG units in the utility grid. This solution will bring a reduction in the fossil fuel dependency and an increment in the efficiency of the overall electric grid. Although most of the studies performed in the literature mainly focus on AC and DC microgrids, hybrid AC/DC systems are an interesting solution as they combine the advantages of the previous two configurations in chapter 4.

5.2 Future Work

Microgrid penetration is currently growing across the globe, leading to various challenges and opportunities. The review comprised of an introduction to microgrids, their components and associated benefits, and a review of applications in enhancing grid performance, which further followed by studies on microgrids economics, operation, control, protection, and communications. Potential areas of research to further advance studies on AC, DC, and hybrid microgrids include applications to difference types of microgrids such as community, remote, etc., the utilization of new technologies in microgrid operation and control such as smart inverters, and the application of the microgrids in grid support for example ancillary services.

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