Hyacinthe Nshuti

Centralized and Decentralize Control of Microgrids

School of Technology and Innovations
Master’s thesis in Smart Energy

Vaasa 2022

UNIVERSITY OF VAASA
School of Technology and Innovations

Author:	Hyacinthe Nshuti
Title of the Thesis:	Centralized and Decentralize Control of Microgrids
Degree:	Master of Science in Smart Energy
Programme:	Smart Energy
Supervisor:	Kimmo Kauhaniemi
Evaluator:	Hannu Laaksonen
Year:	2022 Pages: 67

ABSTRACT

Microgrid can be seen as an important controllable sub-system in future power systems. As a part of distribution network, the microgrid can operate in grid-connected or islanded mode to supply its local loads, and it consists of different renewable and non-renewable distribution generations that are connected to the system through power electronics (PE) interfaces. However, the control of microgrids is one of the important issues to focus on in order to overcome the challenges raised by high penetration of of renewable energy sources (RES). Depending on the responsibilities assumed by the different control levels, the microgrid can be controlled in centralized or decentralized modes. In centralized approach, the microgrid central controller (MGCC) is mainly responsible for the maximization of the microgrid value and optinization of its operation, and the MGCC determines the amount of power that the microgrid should import or export from the upstream distribution system by optimizing the local production or consumption capabilities. However, the MGCC should always consider the market prices of electricity, grid security concerns and ancillary services requested by the DSO when taking decisions. In this case an optimized operating scenario is realized by controlling the microsources and controllable loads within the microgrid, where non-critical, flexible loads can be shed, when profitable. Furthermore, the actual active and reactive power of the components are monitored. When a full decentralized control is implemented, the Management Center (MC) takes responsibilities and it competes or collaborates to optimize the production, satisfy the demand and provide the maximum possible export to the grid but all is done by considering the real time market prices. This thesis discusses the concepts of centralized and decentralized control of MG, where the main chapters introduce different control methods and PE interfaces that are involved in the microgrid control, while the final work presents simulation models that demonstrate how microgrids are controlled through inverters and the results. Using MATLAB/Simulink environment, PQ and V/f control modes of inverter are simulated and the results are discussed to point out their significant effect on balancing the voltage magnitude, maintaining the frequency and power sharing.

KEYWORDS: Centralized control, Decentralized control, Local controller, Central controller, Upstream network interface.

Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AC	Alternating current
ACE	Area control error
AVR	Automatic voltage regulation
CPU	Central processing unit
CSI	Current source inverter
DC	Direct current
DER	Distributed energy resources
DG	Distributed generations
DHT	Distributed Hash Tables
DE	Distributed energy
DNO	Distribution network operator
DS	Distributed source
DSO	Distribution system operator
EES	Electrical energy storage
EMM	Energy Management module
ESCO	Energy Service Company
ESS	Energy storage systems
ESU	Energy Storage Unit
EPS	Electrical power system
EV	Electrical vehicles
GI	Generalized integrator
GSI	Geographical information systems
HC	Harmonic compensator
IC	Integrated circuit
IDs	Identifiers
IGBT	Insulated-gate bipolar transistor
ICT	Information and communication technology
ISA	International society of automation
LC	Inductor-capacitor

LC	Local Controllers
LVDS	Low voltage distribution systems
LVRT	Low voltage ride through
MATLAB	Matrix laboratory
MPPT	Maximum point of power tracking
MC	Management center
MG	Microgrid
MGCC	Microgrid central controller (MGCC)
MAS	Multi-Agent system
MV	Medium voltage
OMDG	Operation and management system of the distribution grid
P2P	Peer to peer
PCC	Point of common coupling
PI	Proportional integral
PID	Proportional integral directive
PLL	Phase lock loop
PE	Power electronics
PR	Proportional resonant
PCM	Protection coordination module
PV	Photovoltaic
PWM	Pulse width modulation
RES	Renewable energy sources
RMS	Root mean square
SMC	Sliding mode control
SOGI	Second order generalized integrator
SCIG	Squirrel cage induction generator
SM	Structured Model
STS	Static Transfer Switch
SG	Synchronous Generator
THD	Total harmonic distortion

UCM	Unstructured Centralized Model
UDM	Unstructured Decentralized Model
UPS	Uninterrupted power supply
VA	Virtual admittance
VI	Virtual impedance
VSC	Voltage source converter
VSI	Voltage source inverter
WT	Wind turbine

1 INTRODUCTION

A micrigrid (MG) is a group of renewable and non-renewable distribution generations (DGs) and interconnected loads. The distribution generations also known as distributed energy resources (DERs) include generators and energy storage systems (Laaksonen, 2011). The microgrid acts as a controllable entity with respect to the grid, and it is capable of operating in both grid-connected and islanded modes. By operating under the two different modes, the flexibility of the microgrid can be achieved. When a microgrid is operating in grid-connected mode, it injects or is supplied an amount of power to/from the grid, and depending on the demand the power from the grid and local DGs is send to the loads. On the other hand, when the MG is operating in islanded mode, the local DGs supply the power to the loads. It is essential to note that in most cases, the MG is operating in grid-connected mode, and the islanded mode is the result from an intentional disconnection from the grid for example when the maintenance is due, or forced disconnection due to the fault in the network (Bevrani et al., 2017, p.129).

High increase utilization of different DGs in microgrid brought quite plenty of advantages, but also plenty of drawbacks in control, operation and power quality aspects. Therefore, the constraints to connect the DGs of a microgrid to the main grid such as ride-through capability, voltage regulation, power quality issues and total harmonic distortion (THD) should be respected as mentioned in IEEE 1547 standards (Zakaria et al., 2019). Some of the DGs benefits are as follow:

- Improved reliability and outage resiliency
- Cost optimization for dispatching DGs and loads
- Diversification of energy sources
- Energy efficiency and demand response
- Ancillary services

According to Bevrani et al. (2019), most of the DGs in microgrid are interfaced to the grid by PE converters, and these converters are conventionally single-phase two level, three-phase two level or three-phase three level voltage source converters (VSCs). PE converters are used to achieve a coordinated and optimized control of MG. In case of island mode operation, the mentioned coordinated power control is performed between the DGs. Moreover, when the MG is disconnecting from the grid, a smooth control is implemented so that the power quality is maintained, and the losses are reduced. When the MG is connecting to the grid, a smooth control and a proper synchronization between MG and the main grid are implemented.

1.1 Background and Motivation

Nowadays, the increase in electricity demand, utilization of renewable energy, power quality and economic constraints of generation expansion have led to the popularity of both AC and DC MG as a sustainable solution, and thus a high-quality control of supplied electricity is extremely important. However, the control of DC microgrid can be more challenging than the control of AC microgrid due to the absence of frequency in DC microgrid, and is difficult to implement the power frequency droop characteristic, which is popular in AC systems. MG control subject can be divided into three parts such as upstream network interface, microgrid control and protection, and local control. The upstream network interface decides whether the MG is able to operate in grid-connected or islanded mode. It makes decisions for markets participation and coordination with the upstream network. The MG control and protection part includes voltage and frequency regulation, real and reactive power control, load forecasting and scheduling, MG monitoring, protection and black start. the local control part includes primary voltage and frequency regulation, primary real and reactive power control for each local DG and energy storage unity (Gao et al., 2015).

MG control can be also classified as centralized or decentralized control according to the mechanism in place. When a MG is operated in a centralized way, the microgrid central controller (MGCC) has the responsibility for maximization of the microgrid value and optimization of its operations. By using market prices of electricity and based on the grid security concerns and ancillary services, the MGCC determines the amount of power that the MG shall import or export and this is done by optimizing the local production or consumption capability. When a MG is operated in decentralized way, each DG works freely utilizing measured local signals. In this case, the main responsibility is given to the management center that compete or collaborate to optimize their production, satisfy the demand and provide the maximum possible export to the grid considering the current electricity market prices.

1.2 Research objectives

The main objectives of this thesis is to investigate, analyze and discuss the concepts of centralized and decentralized control of microgrids.
Sub-objectives are:

- To get proper understanding of microgrid control mechanisms
- To identify different control strategies and to understand how PE interfaces are involved in microgrid control.

1.3 Structure of the thesis

This thesis surveys different control methods and strategies applied in microgrids. It introduces the concepts of centralized and decentralized control mechanisms in MG and demonstrates the control strategies with MATLAB/Simulink simulation models. The thesis is divided into seven chapters as described in the following:

Chapter 1. Introduction: Provides a brief introduction of the topic, and describes the objectives, background and motivation, and the structure of the research.
Chapter 2. Overview of microgrids: This chapter covers the classification of MGs and discusses the importance of the microgrids in general.

Chapter 3. Chapter three discusses different types of inverters and their operations in microgrids.

Chapter 4. This chapter covers the control theory of inverters in microgrids.

Chapter 5. Chapter five discusses in detail the centralized and decentralized control methods.

Chapter 6. This chapter consists of the final work of the thesis. It includes the simulation models that demonstrate the control strategies such as PQ and V/f control techniques.

Chapter 7. Conclusion: It summarizes the research topic and brings the main conclusion and the future scope.

2 MICROGRIDS

2.1 Classification of microgrids

Microgrids can be classified based on the power type, supervisory control, operation mode, phase and application. When the power type is considered, there are AC and DC microgrids, and when considering the supervisory control there are centralized and decentralized microgrids. Depending on the operation mode, there exist grid-connected and islanded microgrids, while based on the phase there are single and three-phase microgrids. Depending on the application, there are residential, municipality, military etc. microgrids. Figure 1 shows the different classification of microgrids.

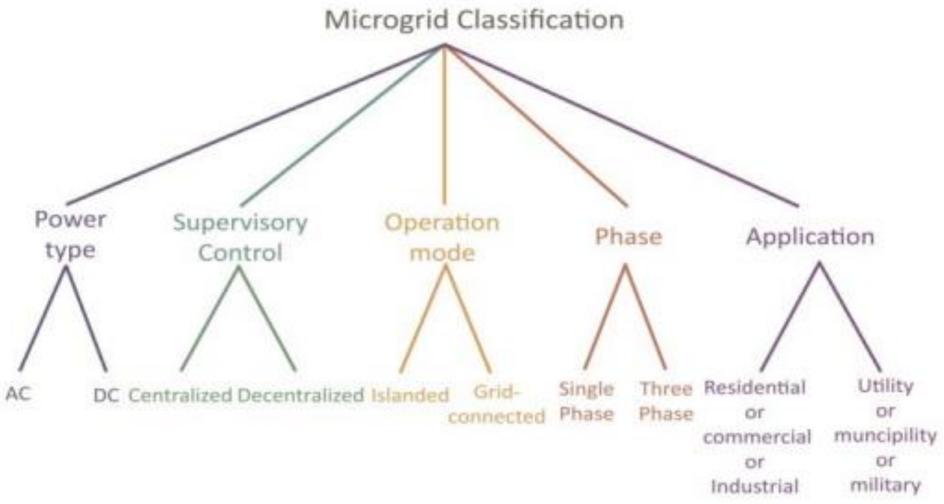


Figure 1 Microgrid classification (Nurunnabi, 2020).

As mentioned above, there are either AC or DC microgrids depending on the power type. For AC microgrid to be integrated into an existing AC power system, it requires a complicated control strategy for the synchronization process in order to maintain the stability of the system where both synchronous and non-synchronous units are usually connected in the same microgrid system. on the other hand, DC microgrids are considered to have a better short circuit protection and a significantly improved efficiency (Gao, 2015). the figure below shows the different types of microgrids based on the power type.

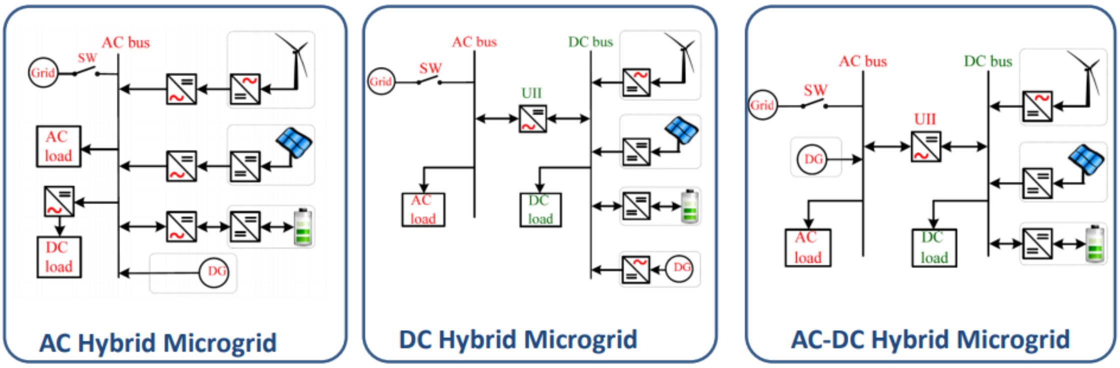


Figure 2 Types of microgrids based on power type (Baboli et al., 2014)

Currently, there is a high increase in DC loads, for example Electrical vehicles (EV) and domestic apparatuses. According to Gao (2015), hybrid AC/DC synchronous/non-synchronous microgrids with multiple b-directional converters will significantly increase in the power system. Figure 3 presents a typical example of a hybrid AC/DC microgrid that includes PE interfaces and multiple DGs.

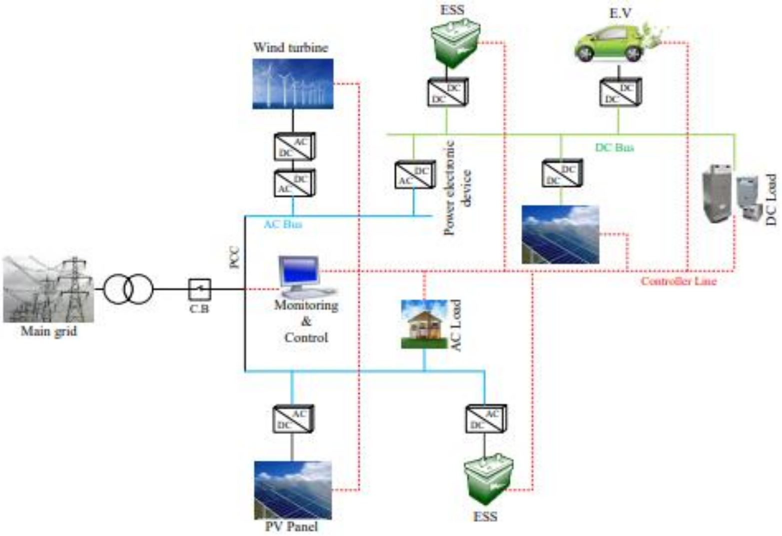


Figure 3 Typical structure of the hybrid microgrid (Palizban et al., 2016)

The interconnection of different types of MGs will form the modern power system which can be called multi-microgrids as it is seen in Figure 4. In the multi-microgrid system, the MGs are connected to the grid through PE converters with either same or different values of voltage and frequency, and in this configuration the MGs are decoupled from each other (Muyeen et al., 2019).

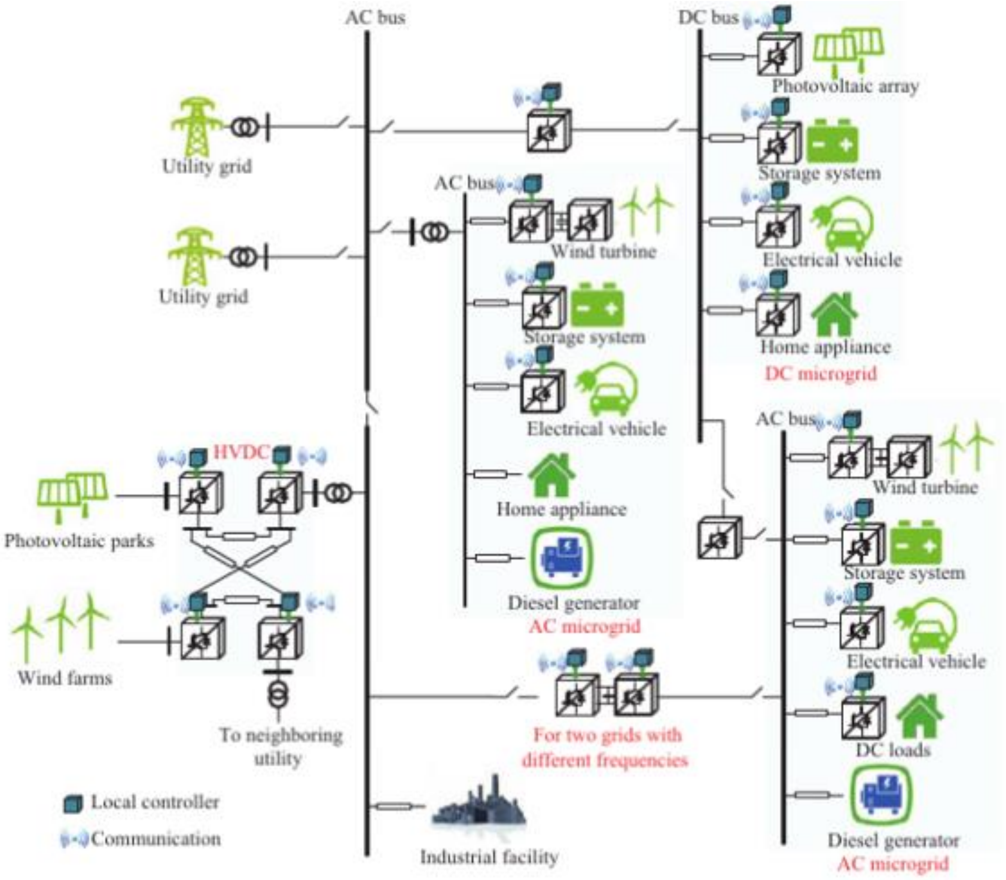


Figure 4 Multi-microgrids: The future power system (Muyeen et al., 2019)

2.2 Need for microgrid control

High increase of microgrids in power systems and integration of DGs units in general brought many challenges that need to be addressed not only in system protection but also in control to make sure the reliability level is increased and other benefits of integrating DGs are exploited. Some of the challenges arise from invalid assumptions typically applied to conventional power systems, while others are the results of stability issues (Olivares et al., 2014). The challenges of stability issues include low inertia, power balance, uncertainty of production, economic dispatch under uncertainty and the transition from grid-connected to islanded mode and vice versa. Those challenges will be dealt with advanced hierarchical control (Muyeen et al., 2019, p. 20).

Some of the benefits of the microgrids, they are seen as controllable loads, which can contribute to peak shaving during the peak demand by reducing their own consumption and this can be done by shedding non-critical loads and supplying more power to the main grid (Gao etal., 2015). However, a proper control strategy should be in place for the microgrid to increase the reliability, and avoid the outage occurances or reduce its duration in case it happens. Since serious power, frequency, and voltage control problems are seen where the renewable energy penetration is relatively at high level, and extremely worse in the isolated island systems with small kinetic energy, many utilities have to update their grid codes to ensure power system security and reliability (Bevrani et al., 2017).

According to Muyeen at al. (2019), renewable based DGs rely primarily on varying ambient conditions and they may not be controllable or predictable accurately. Uncertainty on the demand side caused by unpredictable consumers behaviors creates substantial variations in the realized demand which require more balancing services. Thus, the uncertainties of the load demand and those of unpredictable generations on the side of variable renewable energy sources (RES), plus the high cost of energy storage syatem (ESS) and tight frequency and voltage standards are the biggest obstacles for the application of 100 per cent renewable powered islanded MG. The stated uncertainties should be addressed properly in the nicrogrid design, planning, and real-time operation, and a proper control is a prerequisite for stable and economically operation. The following principal roles of the MG control system are of different significances and time scales, and require a hierarchical control structure to address each requirement:

- Voltage and frequency regulation
- Proper load sharing and coordination of DGs
- Power flow control
- MG resynchronization with the main grid
- Optimization of MG operation costs

3 INVERTERS AND THEIR CONTROL

3.1 Inverter topology

Inverters are used as PE interfaces to connect DGs to the grid, and they are of different types and different roles. For grid connection, most of available commercial power electronic converters are based on voltage source two level PWM (Pulse width modulation) inverter (Sharkh et al., 2014, pp. 4-5). Those type of inverters have an LCL filter which is known to be smaller in size than the normal filter L, but the LCL filter requires a more complex control system to manage the LC resonance. The impedance of LCL filter is too low and it provides a path for current harmonics and as consequence, the THD (Total harmonic distortion) tends to be high. To solve that problem, the feedback controller gain is increased in the current controlled grid connected converter even if this is challenging to do so and maintain the system stability. Figure 5 seen below shows a two-level grid-connected inverter with an LCL filter.

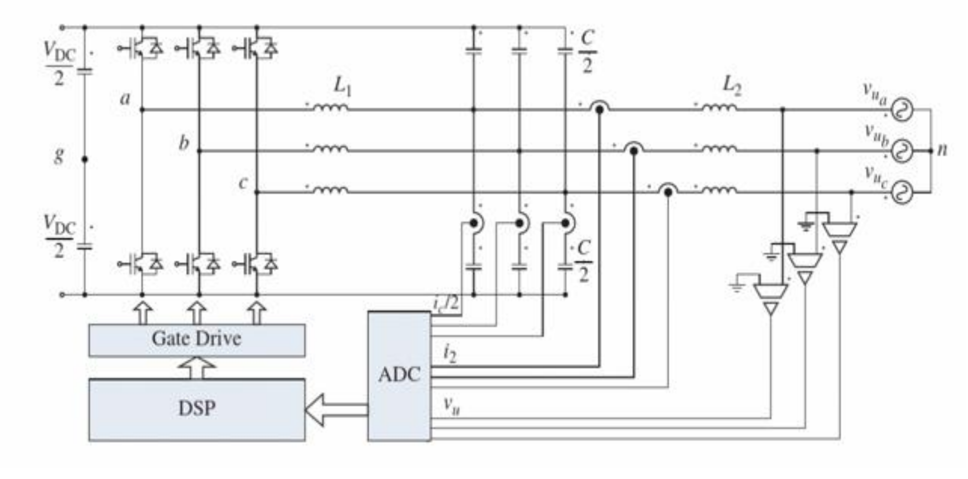


Figure 5 Two-level grid-connected inverter with an LCL filter (Sharkh et al., 2014)

Some other inverters with different filter topologies exist, and apart from the stated inverter above, a mult-level converter is also known for its advantages including the capacity to reduce the voltage step changes, acceptable size and the low cost. A multi-level converter is shown in the Figure 6 below and it may be either of type NPC or cascaded.

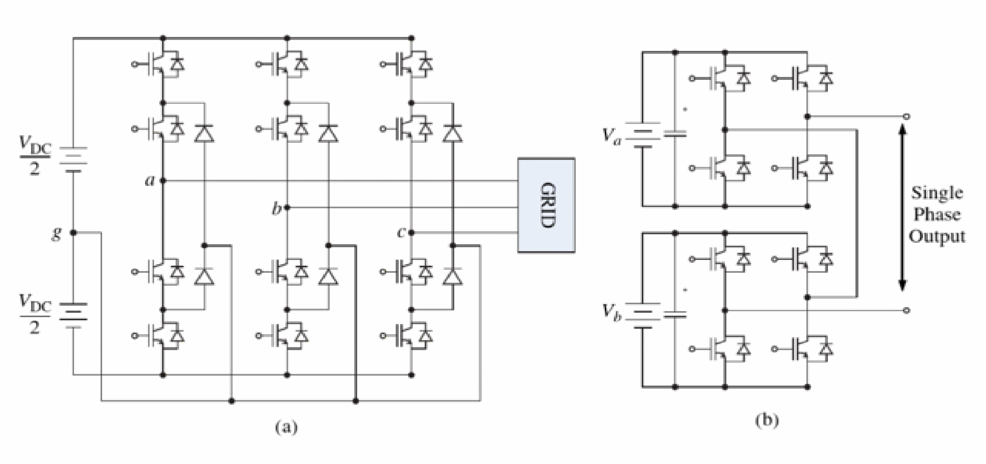


Figure 6 Multi-level voltage source inverter a) NPC and b) Cascaded (Sharkh et al., 2014).

Another example is an interleaved converter shown in Figure 7. An interleaved converter has two channels and can operate as an alternative to the multi-level voltage source inverter.

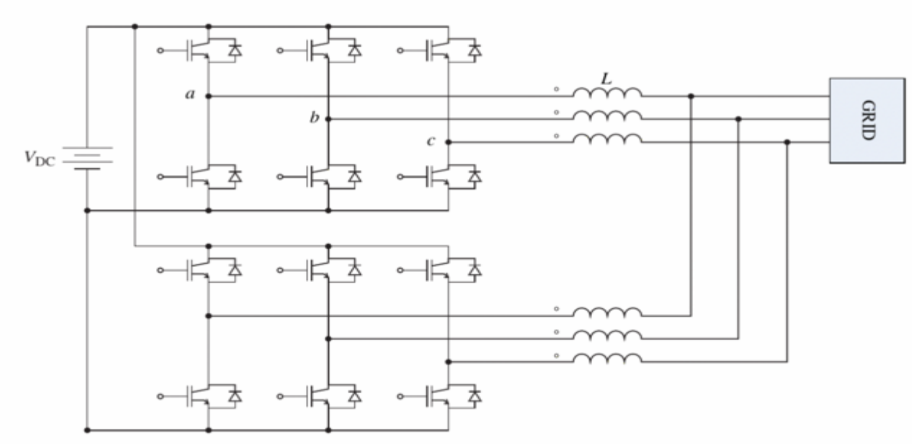


Figure 7 Interleaved converter with two channels (Sharkh et al., 2014, pp. 4-5).

Nowadays, the intelligent PE interfaces used to connect DGs in microgrids are technologically on the advanced level. They consist of inverters that can be classified as current source inverters (CSIs) and voltage source inverters (VSIs). The CSIs have an inner current loop and phase locked loop which allow them to stay synchronized with the grid, while VSIs have the inner current loop and an external voltage loop. Furthermore, the CSIs are commonly used when is needed to inject the current into the grid, and VSIs are more needed in islanded microgrid to keep the voltage stable. VSIs have so many advantages, and they usually employ a PLL to stay synchronized and they provide an important performance including ride through capability and power quality enhancement to DGs. However, the VSIs are required to control the exported and imported power to/from the main grid and make the MG stable when operating either in grid-connected or islanded mode. According to Guerrero (2011), The CSIs are often connected to PV or small wind turbines that require maximum power point tracking algorithms, while VSIs are mainly connected to ESS fixing the voltage and the frequency.

3.2 Control of inverter based DGs

The microgrid can operate either in grid-connected or islanded mode, and it is the operating mode of the microgrid that determines the control function of its DGs units. The main control functions of DGs are voltage and frequency control, and active and reactive power control. The DGs control functions can be classified as grid interactive or non-interactive, where the interactive approach involves either dispatch of power or provides the active and reactive power support, while the non-interactive approach involves exporting power (Padiyar et al., 2019, p. 6y). To control inverter based DGs, different methods also have been proposed, and depending on the DG and operating condition, the three main control methods are PQ control, V/f control and droop control.

3.2.1 PQ control

Among the well-known DG control methods, one is PQ control method. the main idea behind this control method is to maintain the active power and reactive power constant while the voltage and frequency deviate within prescribed limits. In short, when the PQ control is implemented, the active power P and reactive power Q are decoupled to achieve an independent control. Therefore, the active power controller maintains the P output constant and equal to the reference value and the frequency variations remain within the acceptable range. On the other hand, the reactive power controller maintains the Q output constant and equal to the reference value, and the voltage variations are kept within the acceptable range.

In PQ control, the inverter injects the power into the microgrid, and in this scenario the injected reactive power corresponds to a prespecified value. The mentioned prespecified value is defined centrally from the MGCC or locally by using local control loop. Thus, the inverter works as a current controlled voltage source and the PQ control does not maintain the voltage and frequency constant. Therefore, an extra voltage and frequency regulator is needed to keep those values within the acceptable ranges. When the MG operates in grid-connected mode, the main power grid is responsible for maintaining the voltage and frequency within the predetermined limits (Gao et al., 2015, p. 12).

3.2.2 V/f control

The V/f control seems to be the opposite of the PQ control method. In this inverter-based DG control method, the voltage and frequency are maintained constant while the active and reactive powers vary within acceptable ranges. For V/f control approach, the inverter is controlled to feed the load with constant and predefined voltage and frequency values, and depending on the type of the loads, the inverter active and reactive power output are defined. In short, when a V/f control is implemented, the inverter emulates a synchronous generator to control the voltage magnitude and frequency (Padiyar et al., 2019, pp. 6y-6z).

3.2.3 Droop control

The droop control method is one of the most powerful control methods used to control the DGs in a microgrid. Figure 8 presents an example of a detailed block diagram of droop control with a virtual impedance. The virtual impedance will not be discussed in this part, and in case anyone is interested in this subject can check out the reference associated with the Figure 8 and learn more.

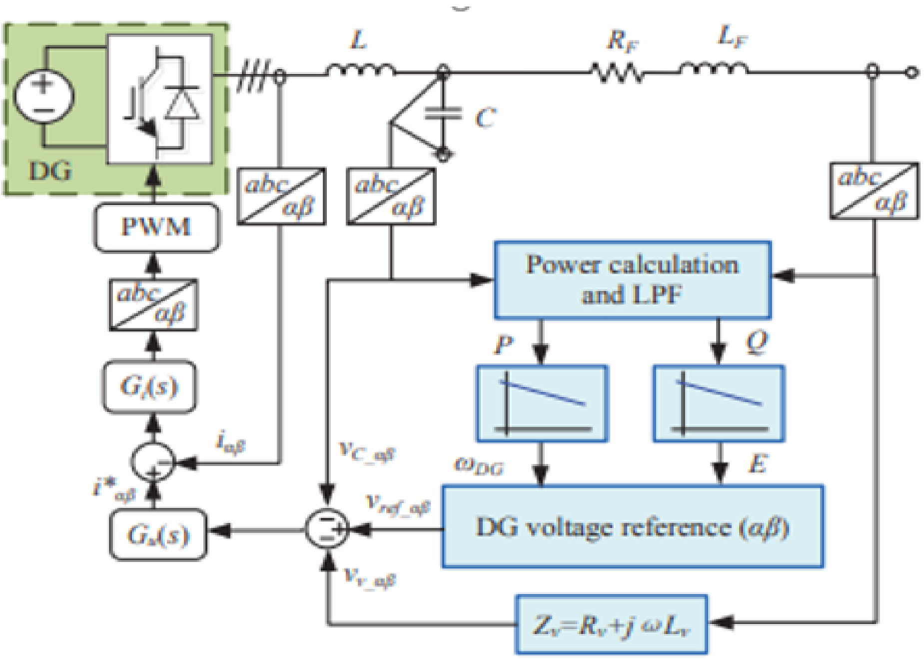


Figure 8 Block diagram of the droop control (Ding et al., 2016).

In droop control approach, the active power variations are associated to the changes in frequency, and the active power is controlled by the frequency droop $(\omega - P)$ characteristic. Similarly, the reactive power variations are associated to the changes in voltage, and the reactive power is controlled by the voltage droop $(V - Q)$ characteristic. The figure below shows both $(\omega - P)$ and $(V - Q)$ droop characteristics.

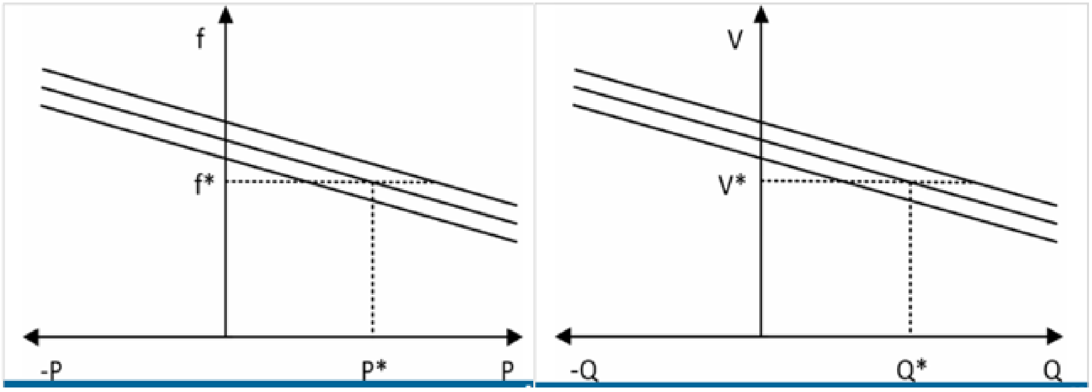


Figure 9 Frequency droop and voltage droop characteristics (Yang et al., 2016).

The reference values of active and reactive power are generated using $(\omega - P)$ and $(V - Q)$ droops as follows (Alam et al., 2016):

$$P_{ref} = \frac{1}{Kp}(\omega^0 - \omega) + P^o \qquad (1)$$

$$Q_{ref} = \frac{1}{Kq}(V^0 - V) + Q^0 \qquad (2)$$

where P_{ref} and Q_{ref} are the reference active and reactive power respectively. Kp and Kq are slopes of $(\omega - P)$ and (V-Q) droop characteristics. P^o and Q^0 are prespecified values of active and reactive power generations. ω^0 is the base or initial angular frequency of the microgrid, V^0 is the base rms voltage of the microgrid. ω is the angular frequency while V stands for the rms voltage. In droop control, the reference currents are determined as follows:

$$i_d^* = P_{ref} K_{cp} \qquad (3)$$

$$i_q^* = Q_{ref} K_{cq} \qquad (4)$$

where i_d^* and i_q^* are reference currents. K_{cp} and K_{cq} are proportional current coefficients. The figure below shows different steps of how reference currents are generated.

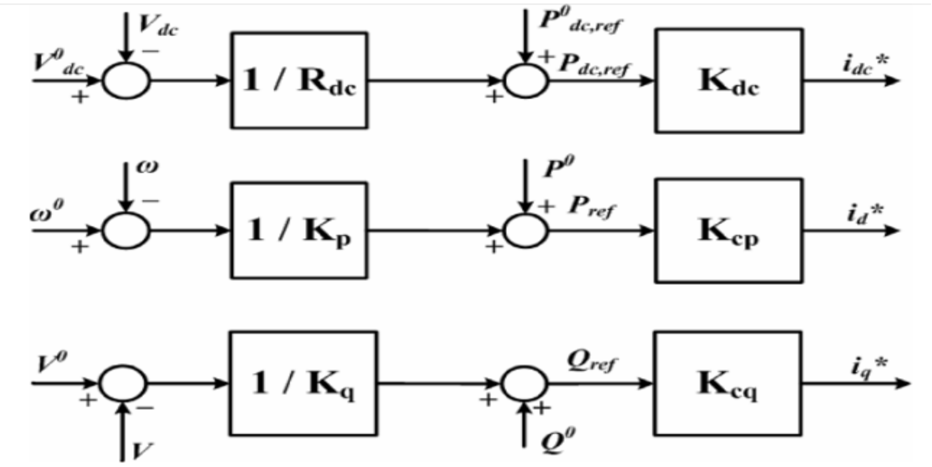


Figure 10 Reference currents generation (Alam et al., 2016).

4 CONTROL OF INVERTERS IN MICROGRID

Microgrids are increasing in the electric power system, and the fact is that this brought a significant impact on the traditional system operation, protection and control. According to Li et al. (2006), a high increase in developing and growth of DGs is the result of the concern for the reliability and the security of the electric power system. Therefore, the ability to provide a proper system control is a crucial service that is needed to keep the point of common coupling (PCC) voltage within the acceptable limits, and MG should ensure the energy security and the local electricity supply for any moment. It is also of importance for the MG to perform the power balance between the production and consumption capacities for the next period. To balance the power, the production is reduced when it is found to be more than the predicted local consumption. In such case, the excess power is dissipated in dummy resistor loads especially when there is an overvoltage situation. On the other hand, when the production is less than the consumption, either some specific DGs will supply the deficit power or some loads will be disconnected from the MG, with exception of some wind generators that can not be dispatched by the MGCC due to the fact that their active and reactive powers are not controllable (Bevrani et al., 2017).

As mentioned in the previous chapters, the DGs of a microgrid are connected to the grid through the PE interfaces. Figure 11 presents atypical example of DG (also known as distributed energy DE) with a PE interface connected in parallel with distribution system. The PE interface consists of inverter, DC-side capacitor with the voltage vdc and dc current source. An LC coupling inductor is used to connect the inverter with the rest of the system. All in all, the PE interface is acting as a compensator which is connected in parallel with the load to the distribution system, and that compensator is connected through the coupling inductor at the point of common coupling (PCC) to regulate the voltage (Li et al., 2010).

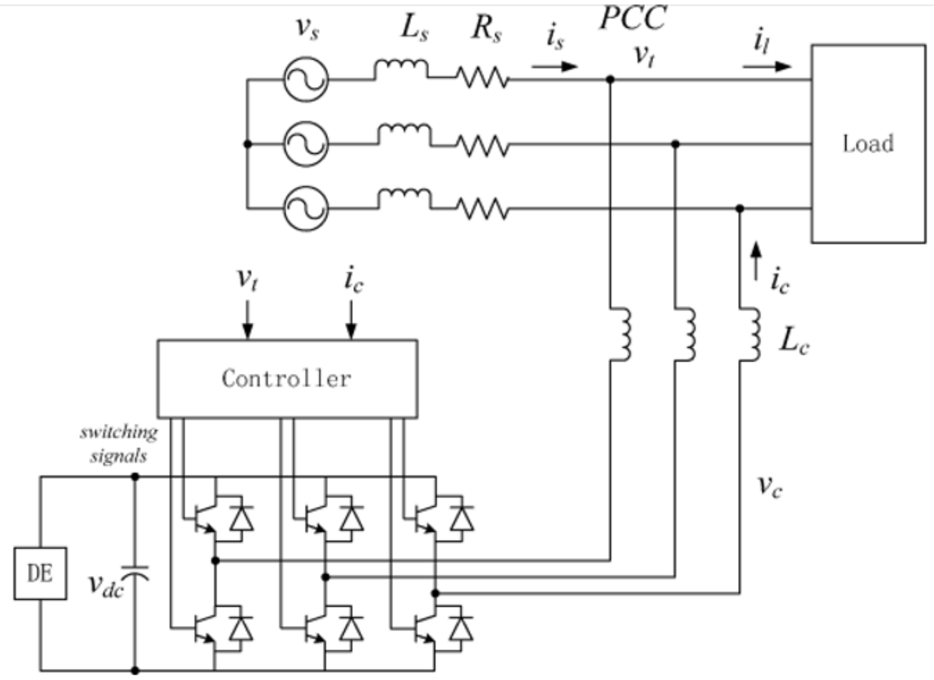


Figure 11 Parallel connection of DG with PE converter (Li et al., 2010).

The PE converters are controlled in different ways depending on the role they play in microgrid. In this section, we discuss grid feeding power converters, grid supporting power converters and grid forming power converters.

4.1 Grid-feeding power converters

Grid-feeding or grid-following converters are widely used in microgrids, because of their greatness when it comes to the point of controlling the microgrid voltage and frequency. For grid-connected mode, many grid-feeding power converters are operated in parallel and they are controlled as current sources because they present a high parallel output impedance. In islanded mode operation, grid-feeding converters can be connected to the microgrid if some other units are operating in grid-forming mode. According to Rocabert et al. (2012), most of the power converters belonging to DG systems like photovoltaic (PV) or wind power system operate in grid-feeding mode, and those converters can participate in controlling the voltage and the frequency by simply adjusting the reference active and reactive power at a higher-level control layer. In other words, in most cases the operation of the stated power converters is regulated by high level controllers of the system which set the reference values of active and reactive powers. High level controllers include maximum power point tracking (MPPT), power plant controllers, etc. Figure 12 presents a typical example of grid-feeding power converter.

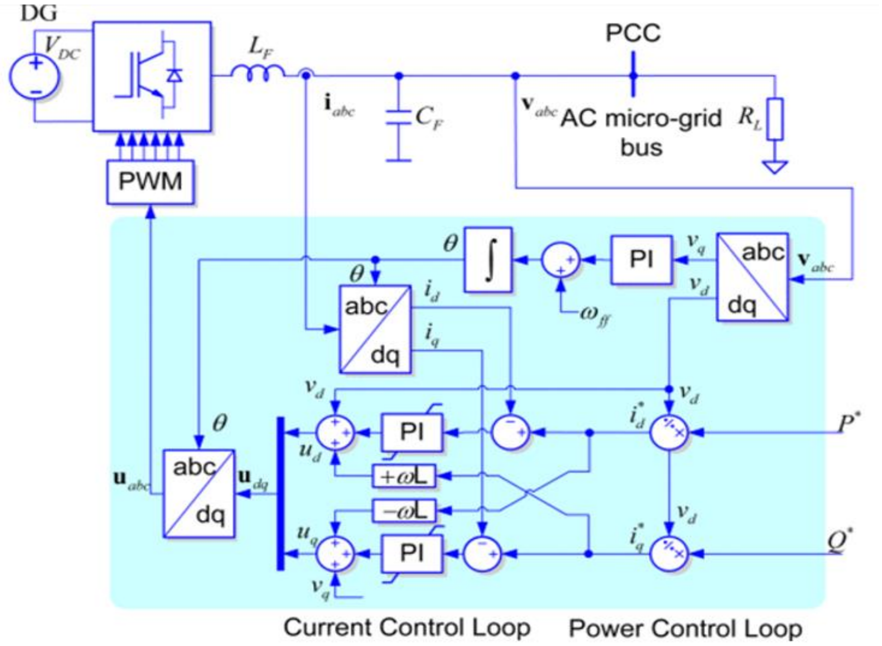


Figure 12 Basic control structure in a three-phase grid-feeding power converter (Rocabert et al., 2012).

When grid-feeding converters are controlled as current sources in a microgrid, they use a phase locked loop (PLL) to achieve synchronization at the PCC. The PCC voltage phase is tracked by the detected phase angle from the PLL. if the q-axis component of the PCC voltage after synchronization is 0, the d-axis of PCC voltage is equal to $\sqrt{2}E$, where E is the rms value of the grid-feeding output. Therefore, the active and reactive power are decoupled so that the reference currents are calculated in dq-frame, and the power flow from the PCC to the grid is controlled at the set point (Chen et al., 2019).

Since grid-feeding power converters are controlled as current sources, they may be vulnerable to the voltage collapse because they lack a dedicated voltage regulator or voltage control loop. And because of the absence of the voltage regulator, the voltage of the DGs will oscillate when there is a significant disturbance (Fahad et al., 2020). When the reference signals reach primary controller, the active and reactive power are regulated to generate the reference currents which may be expressed in dq-reference frame, and thus those currents are regulated to generate the reference voltages which can be used to generate pulse width modulation (PWM) signals. It has been also noticed that the grid-feeding power converters will not be able to continue with a stable operation when the grid voltage is reduced below the certain limits given by the equation below (Chen et al., 2019).

$$V_g = \sqrt{\frac{2P_{ref}^2 X_g}{\sqrt{P_{ref}^2 + Q_{ref}^2} + Q_{ref}}} \tag{5}$$

where V_g is the minimum grid voltage, P_{ref} and Q_{ref} are the reference active and reactive power respectively, X_g is the line reactance. If the grid voltage is below the V_g, the grid-feeding converter will not operate properly, and the equation assumes that the reference active power is equal to the maximum power the converter can deliver (Fahad et al., 2020).

4.2 Grid-supporting power converters

Grid-supporting power converters are used as current sources or voltage sources. Those types of units are used to provide grid supporting functions and to establish microgrids through shared effort of multiple converters. Among the support functions provided by grid-supporting power converters include voltage and frequency support, active and reactive power support, and black start capability. However, the realization of those functionalities depends on the grid feedback measurements. Figure 13 presents a typical example of grid-supporting voltage source converter which is supplemented by a virtual impedance (VI) control loop.

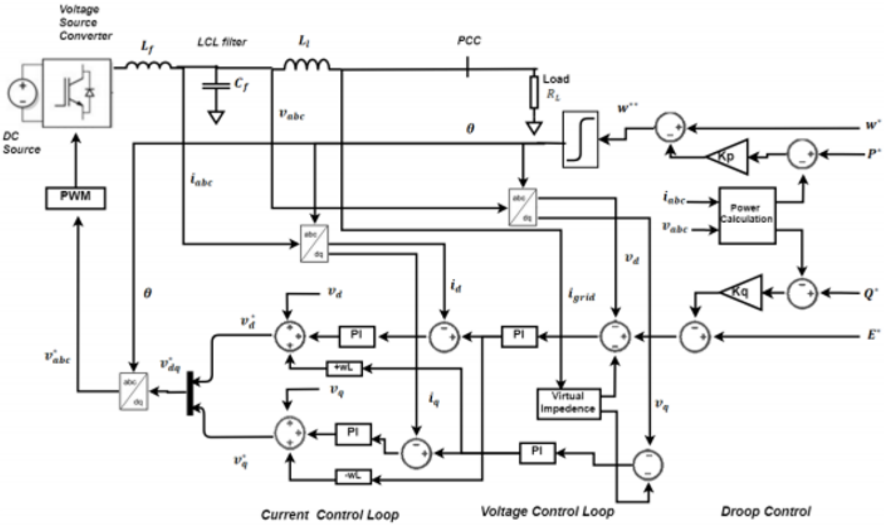


Figure 13 Voltage source grid-supporting converter (Variam et al., 2018).

The latest grid-supporting power converters are supplemented by virtual impedance (VI) and can be split into units with direct VSC voltage control and units with filter voltage control, while the old ones were supplemented by virtual admittance (VA) (Dragičević et al., 2021).

4.2.1 Grid-supporting power converter operating as a voltage source

In microgrid, controlled VSCs have some behaviors of the synchronous generators. In case there is discrepancies between the measured and nominal power, the frequency of the inverter drifts from nominal value, and this is a process realized by the droop mechanism (Kezheke et al., 2018). Therefore, by controlling the active and reactive power delivered to the grid, grid-supporting VSCs regulate the grid voltage and frequency closer to the respected values. Grid-supporting VSCs with voltage control are suitable for island mode, and grid-supporting VSCs with current control are not suitable for island mode because there is no explicit control over the bus voltage (Dragičević et al., 2021).

4.2.2 Grid-supporting power converter operating as a current source

Grid supporting VSCs have similar physical and inner current control structure as grid-feeding VSCs, but they have in addition some outer controllers which allow them to have more functionalities. However, with current control loop grid-supporting VSCs adapt the current reference according to the grid voltage conditions in order to provide active and/or reactive power support to the main grid or microgrid. In this scenario, the outer grid support controller computes the converter side inductor filter current reference that is sent to the inner current controller to ensure tracking, or a direct grid side current is used. The reason behind the active and/or reactive power support is to provide stable voltage amplitude and frequency compensation, virtual inertia emulation, etc. For the grid supporting VSCs, a VA control loop can also be implemented to set the admittance seen by the VSCs (Dragičević et al., 2021).

4.3 Grid-forming power converters

Grid-forming power converters are mostly connected in parallel to grid-feeding power converters in microgrid, and the output of each grid-forming converter is considered to be the reference for grid-feeding converter. The main purpose of those units is to form the microgrid bus voltage and frequency. In general, grid-forming converters are controlled in a closed loop to work as an ideal ac voltage source. In this case they present a low output impedance and an extremely accurate synchronization system is needed to be able to operate in parallel with other inverters. Thus, the power sharing among the grid-forming converters is also a crucial function to be targeted. One typical example of grid-forming power converter is a standby uninterrupted power supply (UPS). In normal conditions, this unit remains disconnected from the main grid, and when the grid fails, the power converter of the UPS forms the grid voltage. The voltage generated by the grid-forming power converter is used as the reference for the rest of the grid-feeding power converters connected to it (Rocabert et al., 2012).

A typical example of grid-forming power converter is shown in Figure 14. It is implemented by using two cascaded synchronous controllers working in dq reference frames. In this example, an external control loop regulates the grid voltage to match its reference value, and the inner control loop regulates the current injected by the converter. The inputs of the mentioned control systems are the voltage V* and the frequency $\omega *$ of the voltage to be formed by the power converter at PCC. It is also noticed in this example that the controlled current following through the inductor L_f charges the capacitor C_f to maintain the output voltage near the reference value given to the voltage control loop.

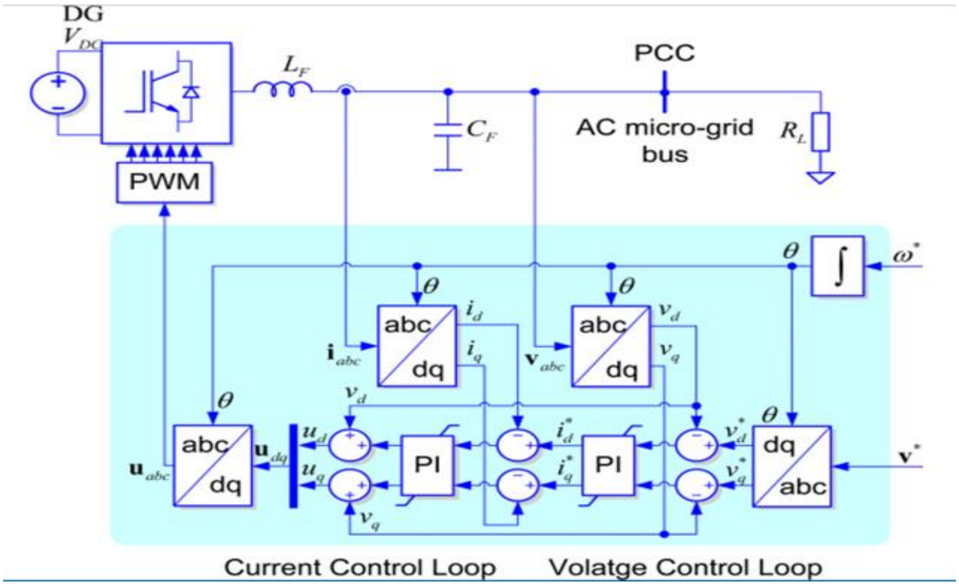


Figure 14 Three-phase grid-forming VSC (Dragičević et al., 2021).

4.4 Control of MGs based on the roles of DGs

4.4.1 Master- slave control

DGs are connected to the AC/DC bus through inverters in microgrid, and microgrids are connected to the main grid through a static transfer switch (STS) or a regular circuit breaker, and they always need to be controlled during their operations. Microgrid can be controlled based on the roles of its DGs, and one of the most known control methods is master-slave control. In this control structure, a microgrid has one inverter acting as the master while the rest inverters act as slaves. The master inverter is considered to be more important unit in microgrid because is responsible of the whole control system. It adopts the PQ control strategy when operating in grid-connected mode, and V/f control strategy when operating in islanded mode (Li et al., 2018). The figure below shows a master-slave control structure of a microgrid.

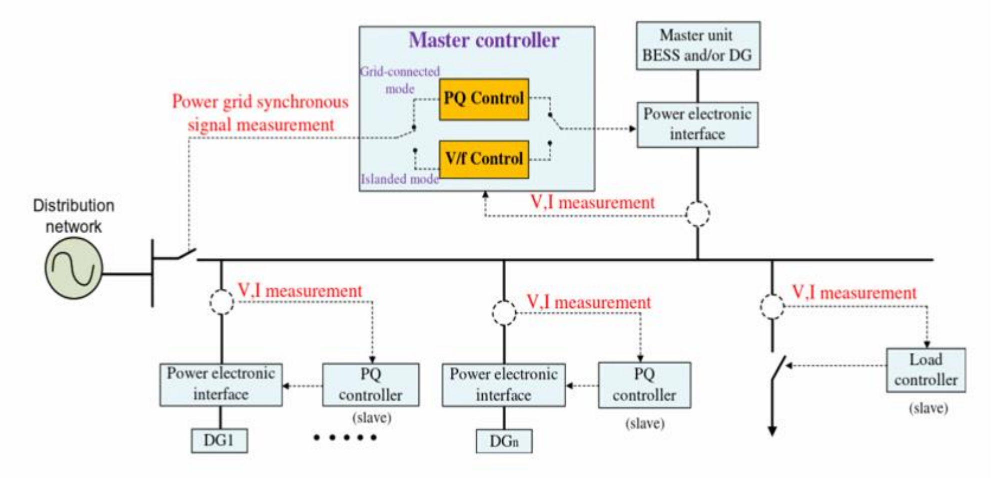


Figure 15 Master-slave control structure (Gao, 2015, pp. 14-15).

Slave inverters also known as slave controllers take corresponding actions based on those of the master controller. When a microgrid operates in islanded mode, one of either DG or ESS of the master unit takes the V/f control role and provides the reference voltage and frequency to the rest DGs and ESSs within a microgrid. In this case, while the master controller is in V/f control mode, the slave controllers are in PQ control mode. In most cases, the MG is operating in grid-connected mode, and voltage and the frequency references are given by the main grid. In such case all controllers remain in PQ control mode, and when the microgrid is disconnected from the main grid one of the DGs will have to switch to V/f control mode and act as a master controller role (Gao, 2015, pp. 14-15).

4.4.2 Peer-to-peer control

Apart from the master slave control method, peer-to-peer control method is also known for its plug and play features. Figure 16 shows an example of a peer-to-peer control structure in microgrid. When a peer-to-peer control method is implemented, all DGs act in the same role and for islanded microgrid each DGs performs a local control according to its own droop characteristics. Therefore, when one of the DGs is disconnected/connected from/to the system, the microgrid will smoothly continue operate without any additional configurations, and this is because during the local transient each DG balances the load variations based on the droop characteristics and the system automatically achieves a new balancing point. However, by adjusting active power, the frequency will be regulated. Similarly, by adjusting the reactive power, the voltage I regulated.

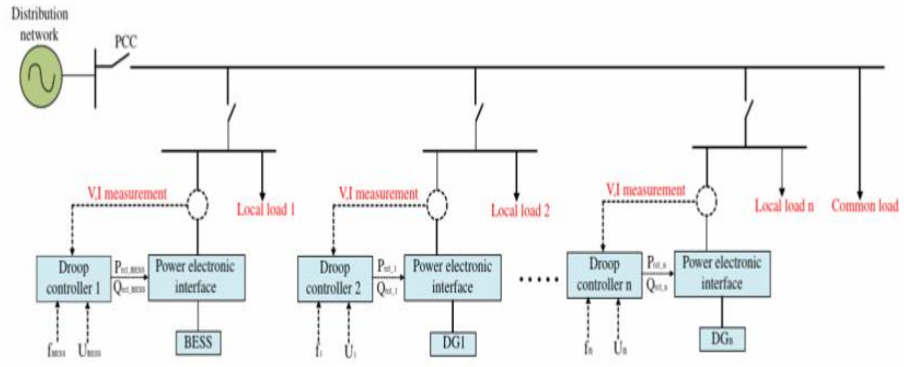


Figure 16 Peer-to-peer control structure (Gao, 2015, p. 17).

4.5 Hierarchical control method

A hierarchical control structure of a microgrid is divided into four different control levels, which are inner control loop (level zero), primary control, secondary control and tertiary control. The purpose of the control levels is to achieve an independent local control to increase the reliability of the power system. In microgrid, the input data of the inner control loop are the output voltage and current from the grid side power converter of DGs. Therefore, accurate references should be in place for an effective management, and those references are passed through sensing and adjusting in the primary control (Palizban et al., 2016, p. 13). In grid-connected operation mode, the secondary control regulates the output power based on the network voltage and frequency while the tertiary control level establishes an interface between the MG and the main grid. The four hierarchical control levels of a MG are shown in the Figure 17, and are discussed in detail in the following pages.

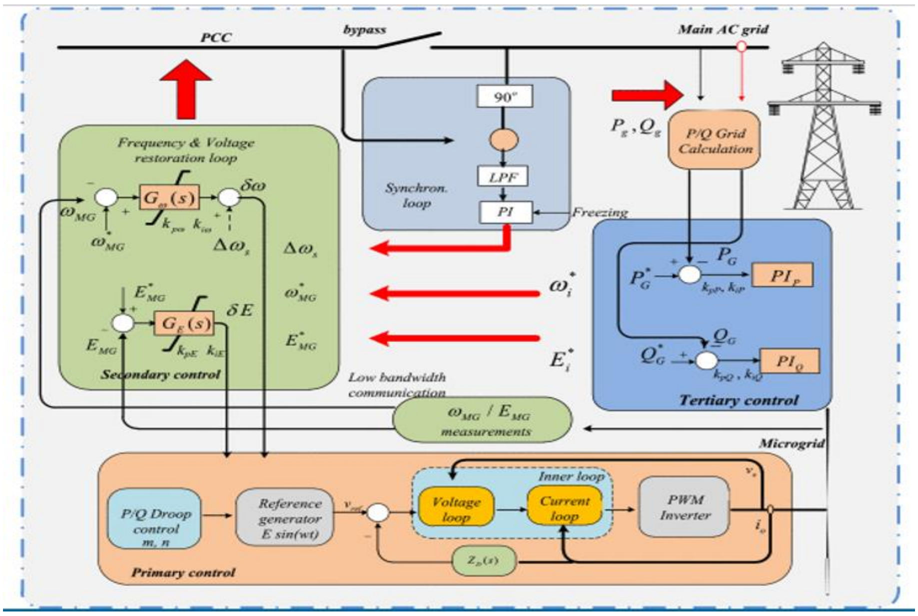


Figure 17 Block digram of the hierarchical control of MG (Zhang et al., 2018).

4.5.1 Inner control loop (Level zero)

The inner control loop also known as level zero is presented in Figure 18 and is the first stage in the hierarchical control structure. Inner control loop deals with the regulation related problems of other control levels, and it is in this stage where the voltage and current implementation, feedback and feedforward synchronization, and linear and non-linear control loops are performed to regulate voltage and current that make the system stable (Variam et al., 2018).

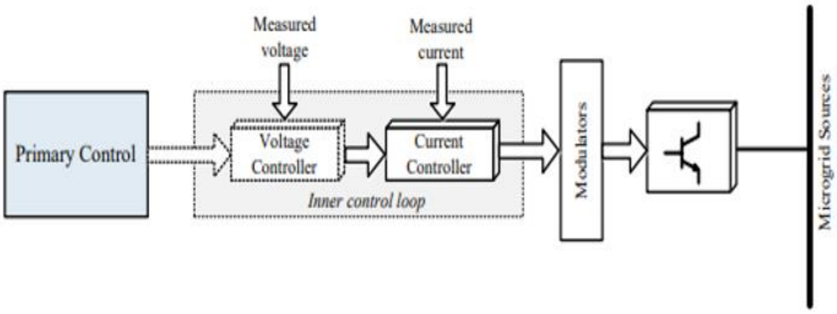


Figure 18 Control block diagram for zer level (Palizban et al., 2016).

4.5.2 Primary control

Primary control level (or level 1) makes the second stage of the hierarchical control structure. It is in this stage the mode of communication is designed, whether it is wired or wireless bus link for control that is needed. The main purpose of the primary level is to make the system more stable. Figure 19 presents a block diagram that shows how a primary control level is implemented.

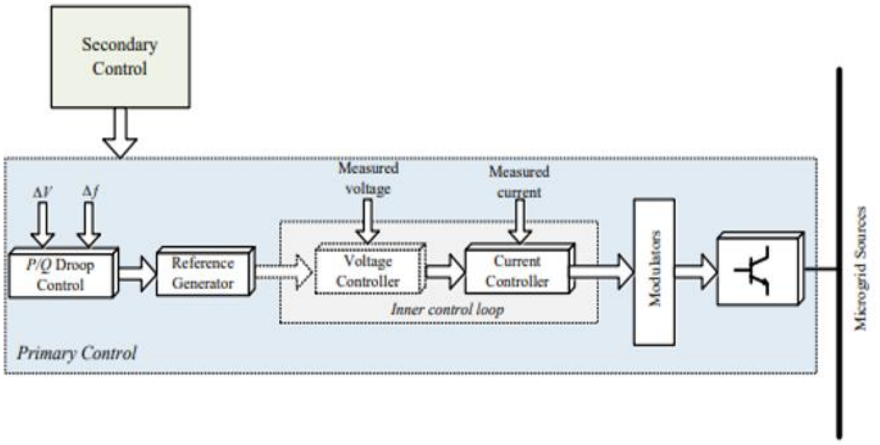


Figure 19 Primary control block diagram (Palizban et al., 2016).

Primary control optimally supplies the active and reactive power of each power converter to the microgrid. Referring to the block diagram above, the primary control level consists of different loops which include a PQ droop control, voltage control loop, and current control loop. Some other proposed structure includes droop control that increases the virtual inertia of the DG by mimicking the governor of synchronous generator, and virtual impedance (VI) control loop that emulates the physical output impedance. The mentioned VI has been extensively used in MG and DGs system in general for the stability purposes, sharing of harmonic distortion and imbalances, fault ride through control, etc. (Dandach et al., 1996). VI has been utilized also in decoupling active and reactive powers supplied by power converters (Zang et al., 2018).

4.5.3 Secondary control

During MG operation, many unplanned situations can occur due to the transients in power generation and variations on the demand side. Therefore, a secondary control is implemented which makes the MG returning to the normal operating conditions by restoring the voltage and the frequency to the required values. It is in this control stage where all information of DGs, ESS, and loads are collected and new references are sent to the primary control level (Palizban et al., 2016). The block diagram of the secondary control is shown in Figure 20, while Figure 21 shows the secondary control in both centralized and decentralized modes.

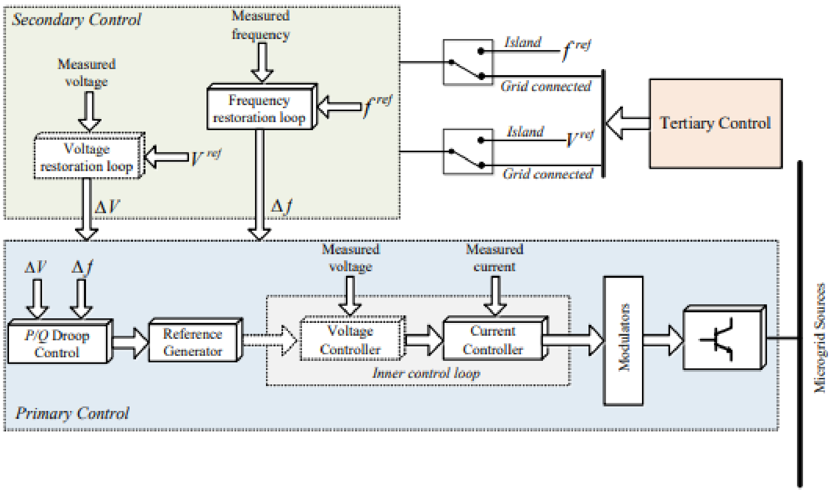


Figure 20 Block diagram of secondary control level (Palizban et al., 2016).

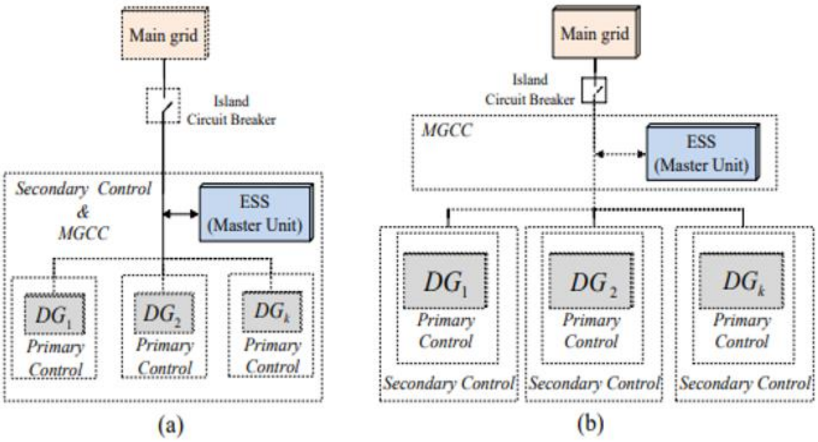


Figure 21 Secondary control level a) Centralized b) decentralized (Palizban et al., 2016).

The main focus of the secondary control is to ensure that the voltage and frequency deviations are regulated toward zero after every change in generation or load sides.

4.5.4 Tertiary control

The final stage of the hierarchical control structure is tertiary control, which is located at the grid level. It is the highest control level and it coordinates operations of all microgrids that interact with each other. A control block diagram of tertiary control can be seen in Figure 22.

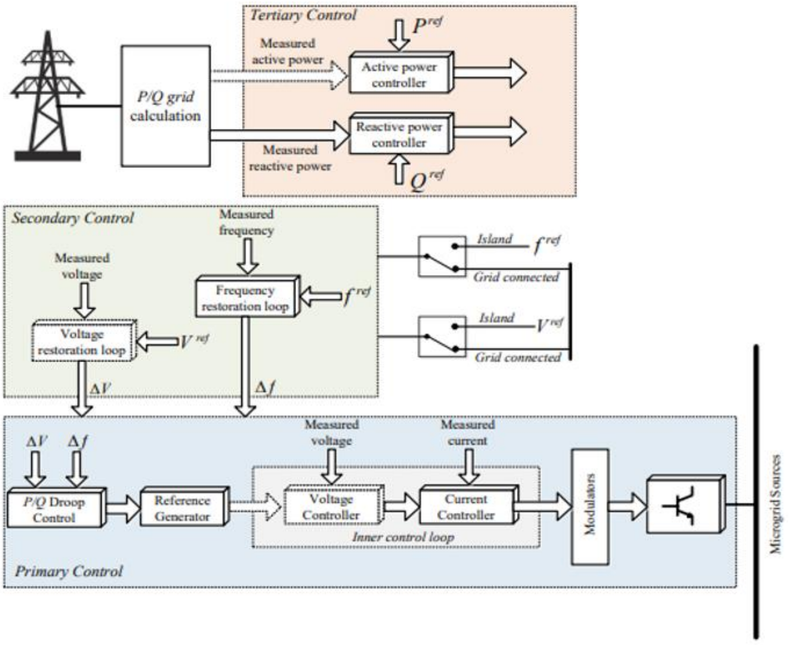
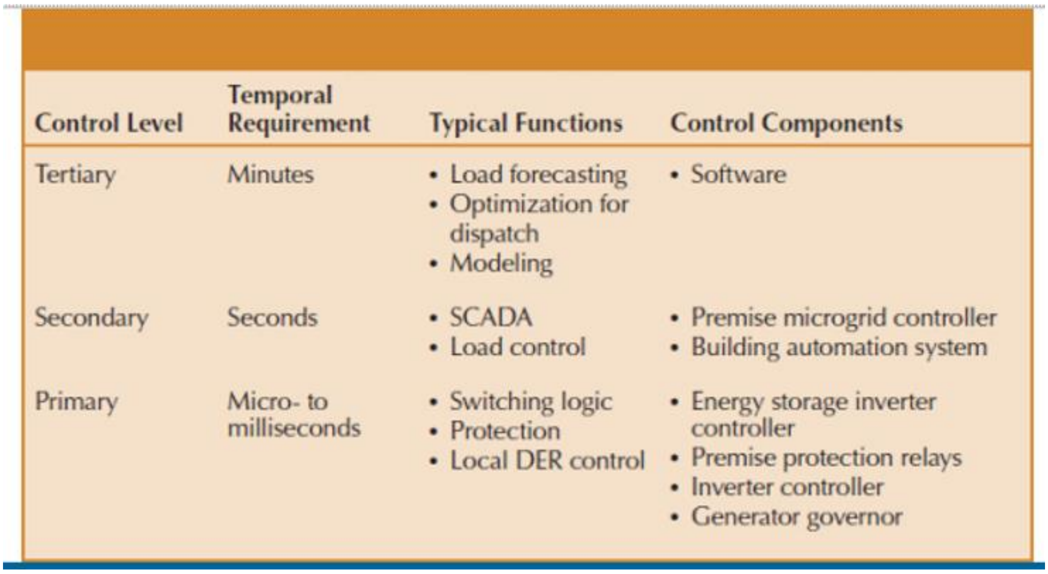


Figure 22 Tertiary control level diagram (Palizban et al., 2016).

Tertiary control stage has a large timescale in order of minutes (Fahad et al., 2019). and the table 1 below describes the functions and controllable components in different control levels.

Table 1 Microgrid control hierarchy (Rojas et al., 2017).



Control Level	Temporal Requirement	Typical Functions	Control Components
Tertiary	Minutes	• Load forecasting • Optimization for dispatch • Modeling	• Software
Secondary	Seconds	• SCADA • Load control	• Premise microgrid controller • Building automation system
Primary	Micro- to milliseconds	• Switching logic • Protection • Local DER control	• Energy storage inverter controller • Premise protection relays • Inverter controller • Generator governor

In conventional power system, the tertiary control level is responsible of the economic dispatch related operations. It is in this stage the network condition and load data are collected and analysed to optimize the power system operations (Begum et al., 2017).

5 CENTRALIZED AND DECENTRALIZED CONTROL

The network frequency must always be restored when an event or frequency deviation occurs in the system. There are many technics to restore the frequency including centralized and decentralized methods. The centralized method is realized by using area control errors on slow timescales, a centralized integral controller, and one-to-all communication (Simpson-Porco et al., 2015). However, the centralized method conflits with the MG paradigm of DGs and the autonomous management. On the other hand, the decentralized method uses a local integral control associated to each inverter (Chandorkar et al., 1993). In such case, the measured local frequency will be assumed to equal to the network frequency. Thus, this control method is too slow to dynamically regulate the network frequency during the rapid load change. Figure 23 shows a frequency restoration achieved by the secondary control.

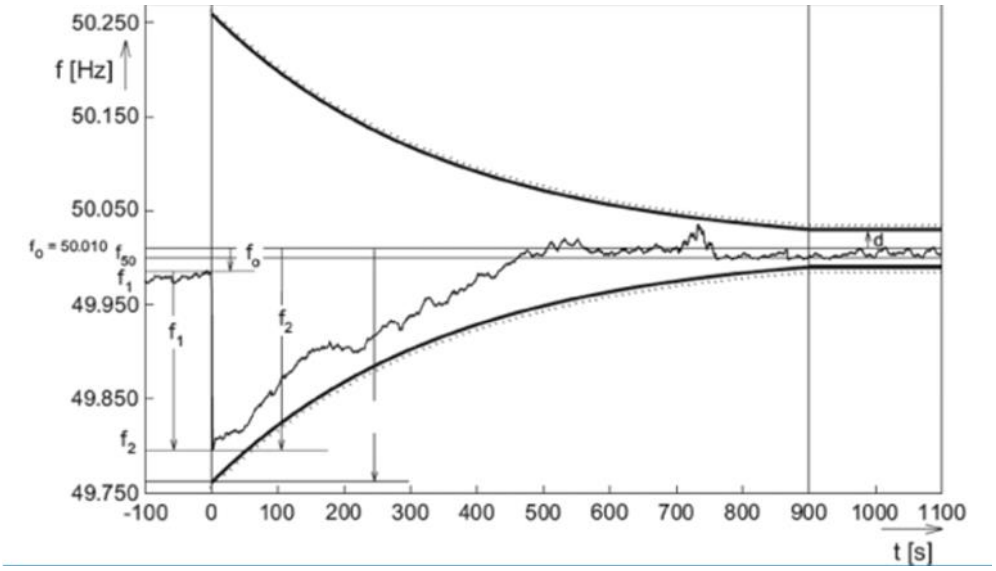


Figure 23 Frequency restoration achieved by the secondary control action (Guerrero et al., 2011).

The network frequency can also be regulated by using a method that introduces a complex communication structure, where all DGs units have to exchange information related to frequency, voltage, active and reactive power, etc. However, this method presents some drawbacks like need of dense communication structure, since all inverters should communicate each other. the controller gain should be finely tuned in order to maintain active power sharing (Bouattour et al., 2013). the voltage regulation has been adopted as a standard for voltage secondary control in MG. Therefore, the voltage is regulated to fixed values by excitation system on the generators side. Moreover, the system controllers regulate the DGs voltages to their nominal values.

5.1 Centralized control

Microgrid can be controlled in a centralized way. In most cases, centralized control is used for islanded microgrid with fixed infrastructures, where the communication network and decision-making hierarchy are simple (Rojas et al., 2017). When a centralized control is implemented, the central master controller that connects to each DG in microgrid collects information from all DGs, then runs the voltage and frequency stability logic, and thereafter based on the results it issues appropriate primary control commands. Furthermore, in centralized control system, the microgrid central controller (MGCC) will maintain the lookup table with updated information related to DGs status and types, generation capacity, voltage and current levels, operation mode, demand, etc. (Nurunnabi, 2020).

The centralized control method has some drawbacks in its operation. If a master central controller fails, control commands are interrupted and not available to DGs and other microgrid assets. Secondary, the power system and the MG infrastructures in general are rapidly developing and new advanced configurations are needed. Therefore, it is challenging to modify the already in place central master controller configurations and settings (Rajos et al., 2017). Another issue, the centralized control method requires dense communication structure, and is not suitable for large area control.

The mentioned MGCC is made up by two essential modules. One is energy management module (EMM) which is mainly responsible for managing voltage, frequency, active and reactive powers and sending operating values to the local controllers. the second module is the protection coordination module (PCM). PCM is responsible for microgrid protection whether the MG is operating in grid-connected or islanded mode. Moreover, PCM should identify the islanding, measure the fault current, and implement the appropriate protection settings to ensure the security of the MG and main grid. The following are functions of MGCC:

- Planning economic production of active and reactive power
- Managing system parameters from DGs, bus, load that are essential for control
- Maintaining the reliability and stability of the network

The figure below describes the principles and decision support tools of centralized control in microgrid.

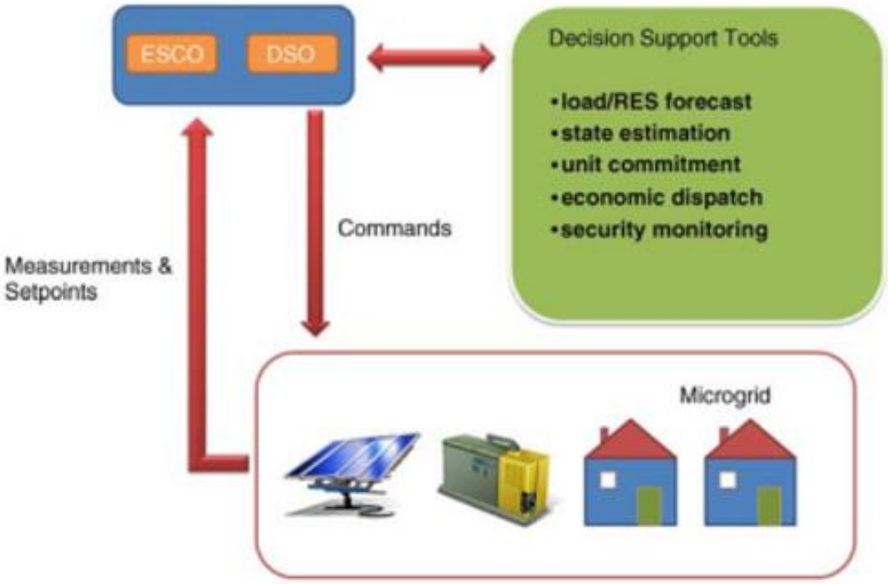


Figure 24 Principles of centralized control (Hatziargyriou, 2014, p. 33).

According to Gupta et al. (2018), centralized control architecture is suitable for optimization functions such as day-ahead scheduling and economic dispatch which is based on the forecasted data and real time power pricing. Talking of power pricing, caramia et al. (2016) have performed optimization of energy cost and real time harmonic voltage compensation of the AC bus, and found that on the demand side, central controllers can optimally respond to the real time grid prices by controlling dispatchable loads (demand response).

5.2 Decentralized control

The decentralized control structure consists of local controllers (LCs), MGCC, and distribution network operator (DNO). It is considered to be a possible solution for integrating as much as possible DGs in microgrid because within this control scheme each inverter coupled DG is controlled freely and various service providers can own the DGs. The LCs responsibilities are much more in a decentralized control than in centralized control method. However, the main grid manages the voltage and the frequency when the MG is operating in grid-connected mode. In such case, the DGs are equipped with the frequency droop features for sharing the active power, and voltage droop features for sharing the reactive power to the microgrid (Nurunnabi, 2020). When the MG is operating in islanded mode, one of the DGs takes responsibilities to govern the microgrid's voltage and frequency, and this is same as master-slave control discussed in Chapter 4.

Decentralized control can use a peer-to-peer communication network between the DGs. In this case, a secondary control layer is present at each DG to collect all measurement information from the DG which are used to produce new appropriate control commands to be sent to the primary control layer which resolves the steady-state errors in voltage and frequency. Moreover, the decentralized control with its distributed structure offers a high level of redundancy and improves the overall secondary control reliability, for example when one unit fails, it can be excluded from the network and the rest will continue to operate with adequate primary and secondary controls in place (Rojas et al., 2017). Figure 25 presents the principles of the decentralized control in microgrid while Figure 26 shows the secondary decentralized control.

Figure 25 Principles of decentralized control (Hatziargyriou, 2014, p. 33).

A completely decentralized control system presents some drawbacks, such as the MGCC is unaware of all actions being executed by the local controllers, since this control system mainly depends on LCs. However, to overcome this problem, a hybrid control system can be implemented and in this scenario the MGCC always will have to recheck the actions executed by LCs, and when something wrong is identified at any local controller level, the MGCC sends a modified control command to that LC (Nurunnabi, 2020).

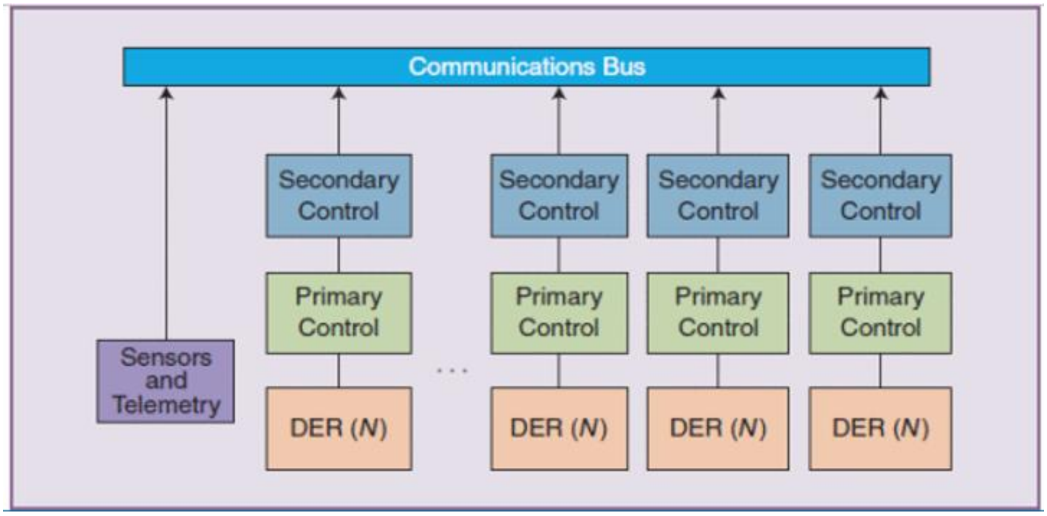


Figure 26 Secondary decentralized control (Rojas et al., 2017).

Nowadays, decentralized control is popular, not only for microgrids but also for the whole power system. It is being designed with advanced technology based on the multi-agent system (MAS), with the idea to introduce an autonomous control process at each controllable unit such as inverter, DGs and loads (Hatziargyriou, 2014, p. 51). Depending on the operation mode of the microgrid, the automated control system has certain level of intelligence to take decisions locally, and LCs should take appropriate decisions to ensure safe and smooth operation of controlled DGs. However, the use of the decentralized control in microgrid provides effective solutions for some specific operational problems, for example, local DGs and loads have different owners, and many decisions should be taken locally and independently (Padiyar et al., 2019, pp. 4-5).

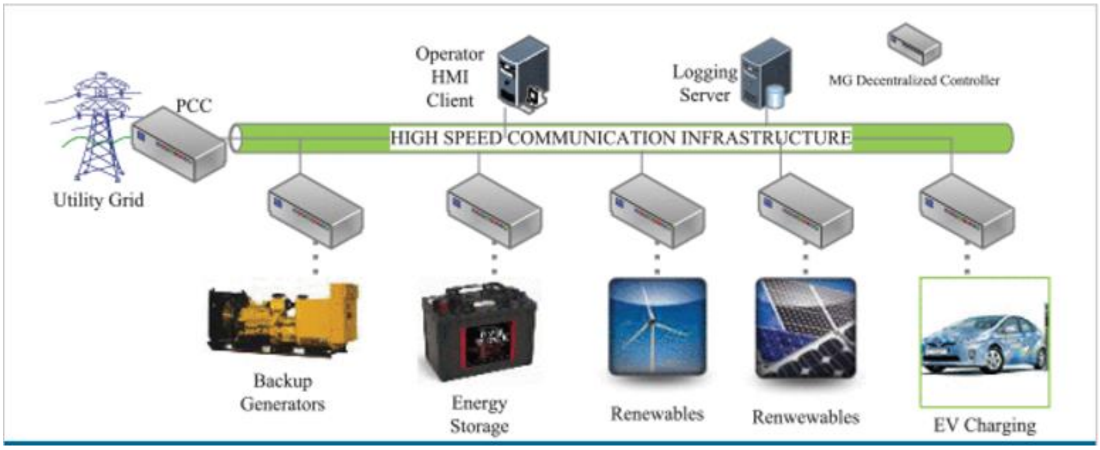


Figure 27 Decentralized control system with communication infrastructure (Bani-Ahmed et al., 2019).

6 MODELLING AND SIMULATION OF DIFFERENT CONTROL TECHNIQUES

This chapter focuses on modelling and simulation of PE interfaces that are used to control the microgrid either in centralized or decentralized control mode. It introduces grid-connected and standalone inverter control strategies, and some examples of how controllers such as PQ and V/f are implemented.

For the first model, a grid-connected inverter is simulated by using MATLAB/Simulink environment, and PQ control strategy is implemented and discussed. The simulation parameters are presented in the table below.

Table 2 Grid-connected inverter simulation parameters

Symbol	**Parameters**	**Value**	**Units**
VDC1	First DC voltage source	500	V
VDC2	Second DC voltage source	500	V
g	Gain	1	-
R_{inv}	On state Inverter resistance	1e-3	Ohm
L_g	Grid Inductance	2	mH
f	Grid frequency	60	Hz
V_{L1}	Fist load rated voltage	380	V
P_{L1}	Fist load real power	50	kW
V_{L2}	Second load rated voltage	380	V
P_{L2}	Second load real power	50	kW
V_{L3}	Third load rated voltage	380	V
P_{L3}	Third load real power	75	kW
S_T	Transformer apparent power	500000	VA

V_T	Transformer Rated voltage	25000/380	V
fsw	Inverter switching frequency Inverter switching frequency	6000	Hz
Ts	Fundamental sample time	1e-6	s
Tsc	Control sample time	5e-4	s
Kp_vd	Proportional term d-axis voltage controller	0.36	
Ki_vd	Integral term d-axis voltage controller	850	
Kp_vq	Proportional term q-axis voltage controller	0.36	
Ki_vq	Integral term q-axis voltage controller	850	

Note: To simplify the simulation, the values are expressed in per unit values

Figure 28 presents the overall structure of grid-connected inverter simulation model. For this model, the structure includes the inverter subsystem, and three real power loads where one of them is connected to the system through a circuit breaker.

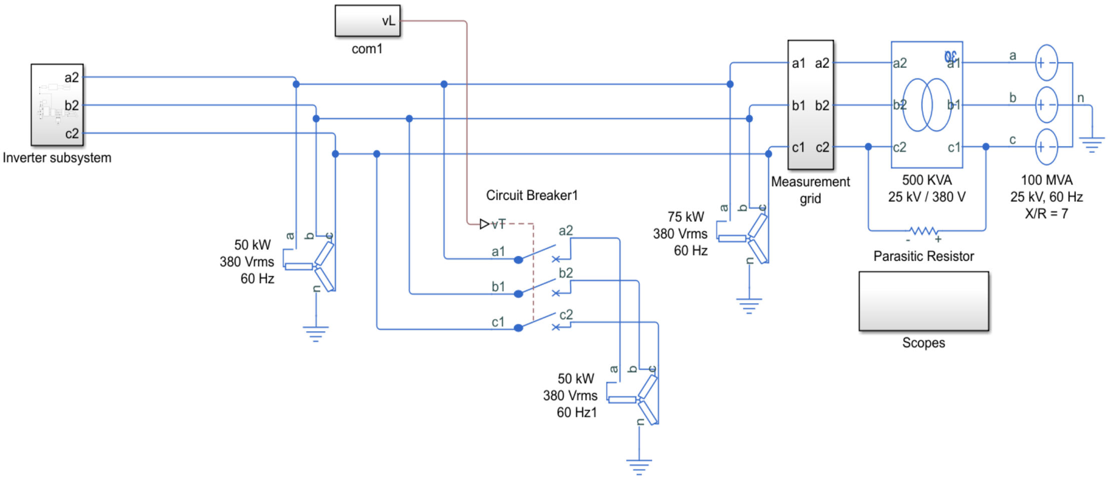


Figure 28 Overall structure of grid connected inverter model

The inverter is shown in Figure 29. The inverter is connected to the grid via measurement device and a filter which is used to reduce the harmonics to acceptable level. In most cases LCL filter is used due to its effectiveness.

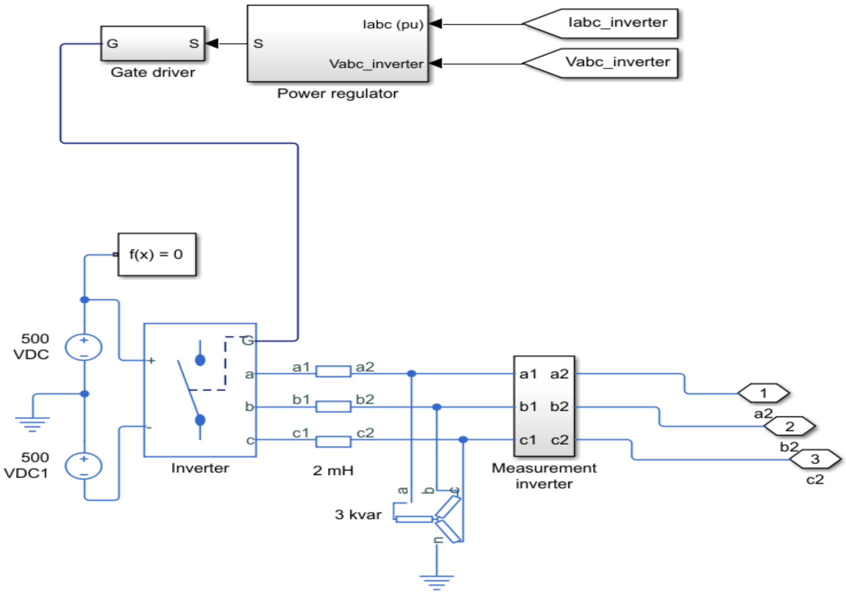


Figure 29 Inverter

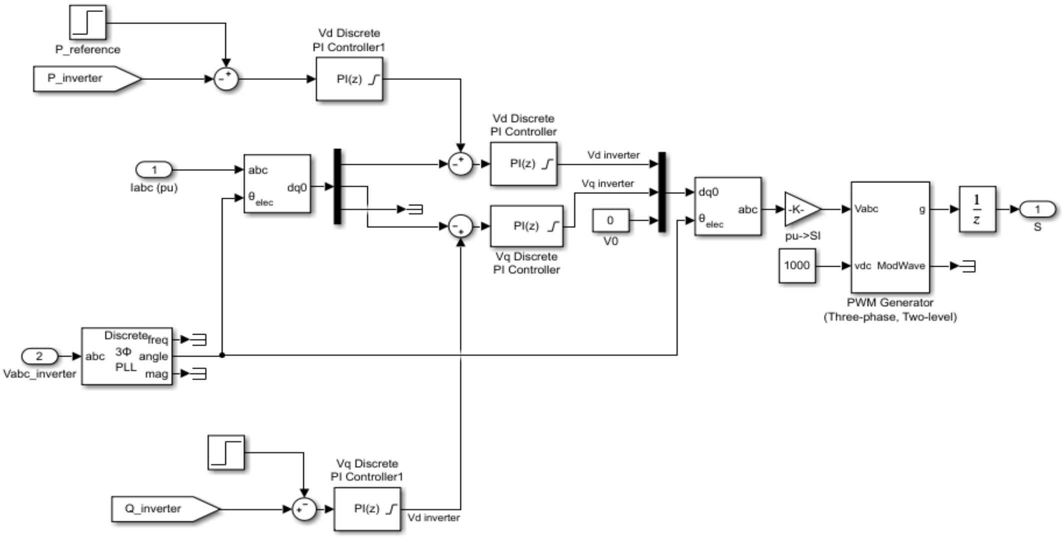


Figure 30 PQ controllers

Figure 30 introduces the PQ controllers. PQ control is implemented to keep active and reactive power constant. For an inverter controlled microgrid, the power is absorbed or injected from/to the grid when working in the grid-connected mode, while the inverter supplies the local loads when operating in islanded mode. In this typical example of grid-connected inverter modelling, P_{ref} and Q_{ref} are set to be 1 p.u and 0.1 p.u respectively. In practice, the mentioned fixed values of active and reactive power (P_{ref} and Q_{ref}) come from the MGCC and are set based on the power needed or the market. The simulation results presented in Figure 31 show that a grid-connected mode with a PQ control is properly implemented. At 0.05s the P reference is raised to 1 p.u, and at 0.1s the Q reference is raised to 0.1 p.u as expected. When an additional load is connected to the system at 0.15s, the inverter continues to supply the set values while the grid supplies the additional load.

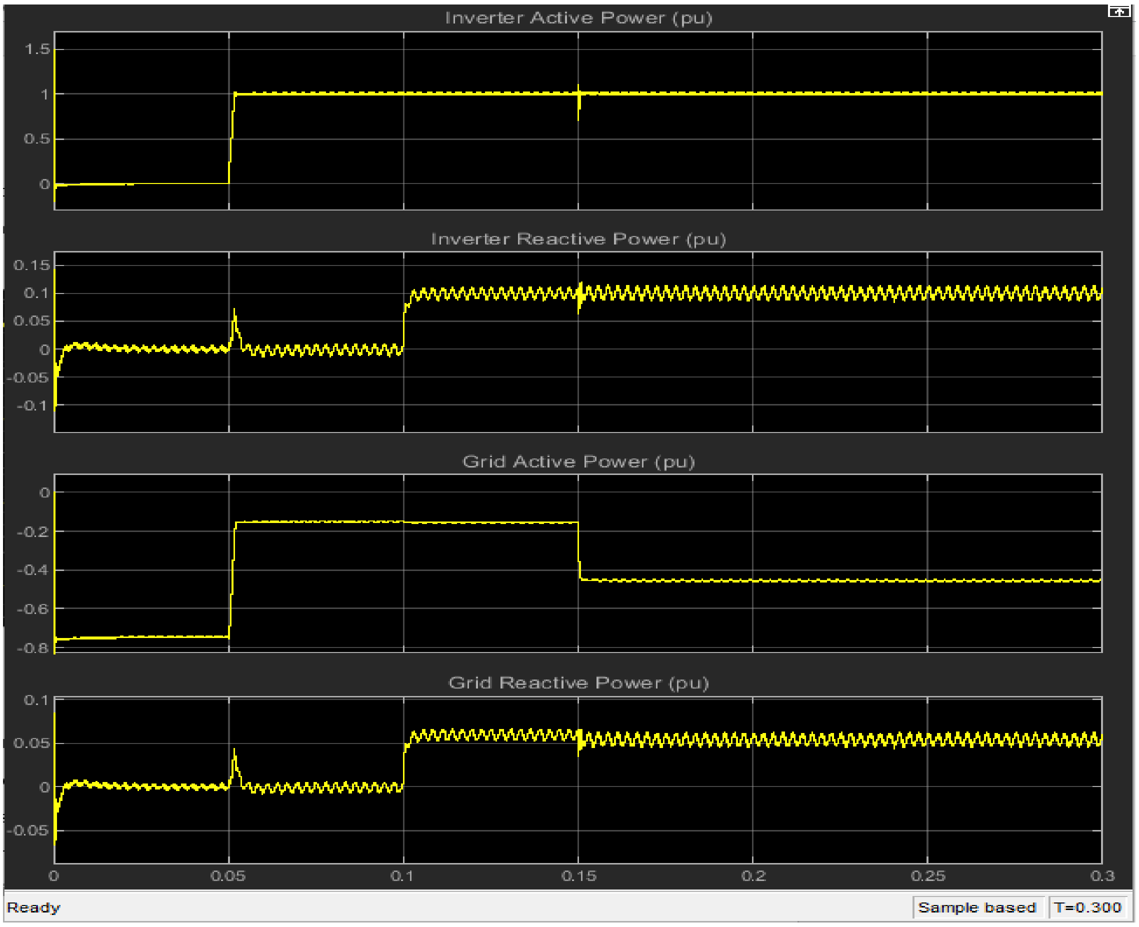


Figure 31 Inverter and grid active and reactive power

The voltage and currents are sensed and fed to the control system to be regulated. In this scenario, the voltages and currents are compared to the reference values, and the errors are sent to the PI controllers. The simulation results show that the voltage control maintains the output voltage sinusoidal and balanced as it can be seen in the figure below.

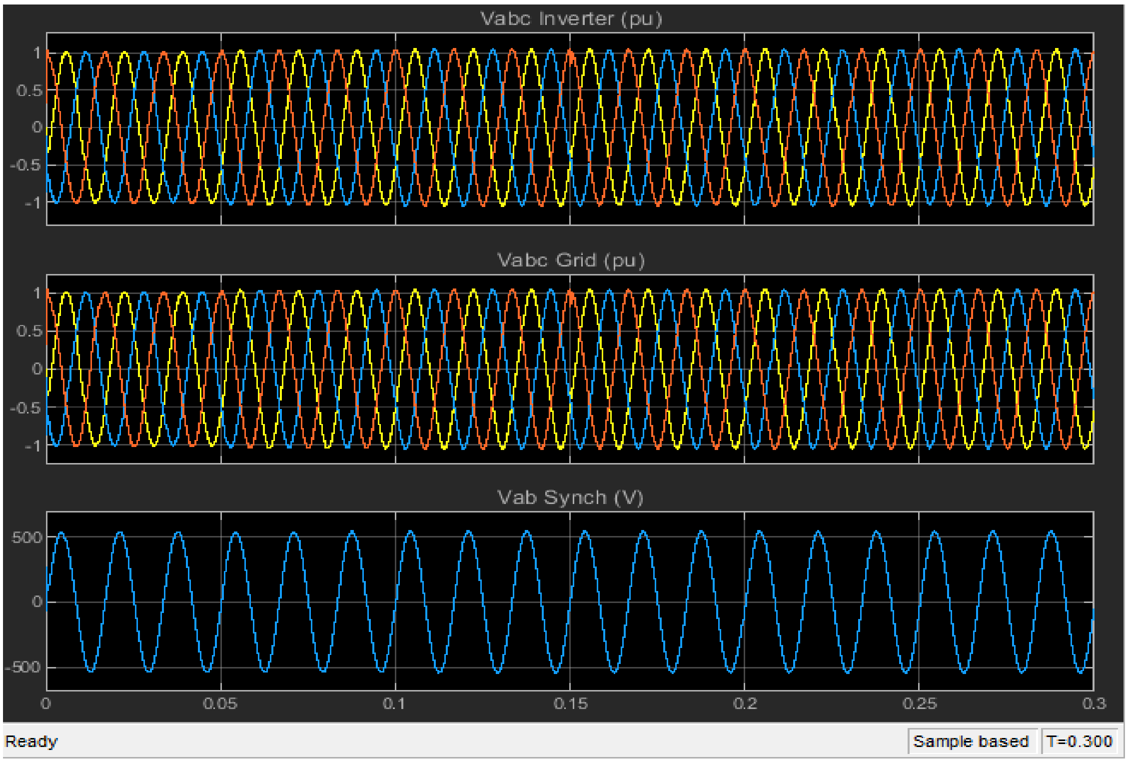


Figure 32 Inverter and grid voltages

For inverter and grid currents, the simulation results show that after the controller reference value changes and connection of the additional load, both inverter and grid currents settled to 0.7 p.u and 0.3 p.u respectively, and they are clean sinusoidal and balanced waveforms.

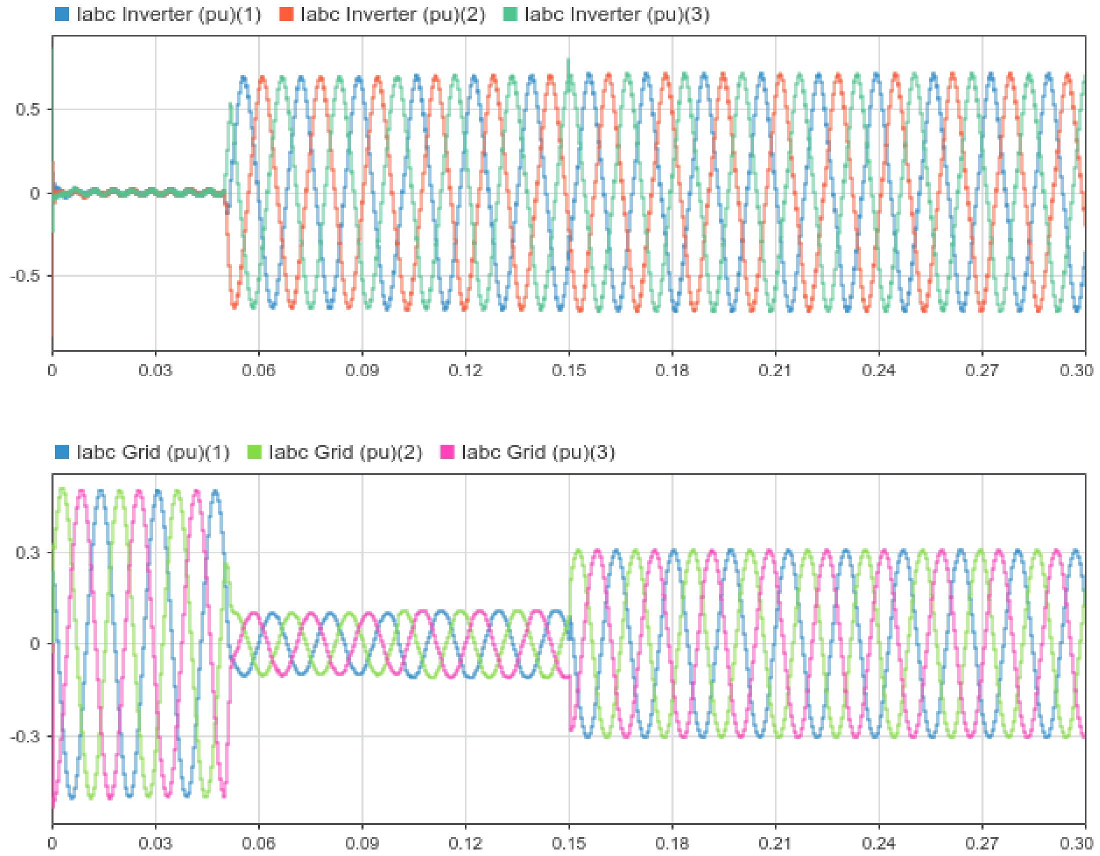


Figure 33 Inverter and grid currents

- Implementation of V/f control in decentralized control mode

In most cases the V/f control mode is implemented in standalone inverter operation. It is considered to be local and practical in decentralized mode. In the V/f control mode, the inverter is controlled and supply to the load with predetermined values of frequency and voltage. Therefore, the voltage and frequency are kept constant while the active and reactive power may vary within acceptable limits. It is important to note that in this case the inverter emulates a synchronous generator and the voltage magnitude and frequency are controlled accordingly. Figure 34 below shows the structure of the standalone inverter.

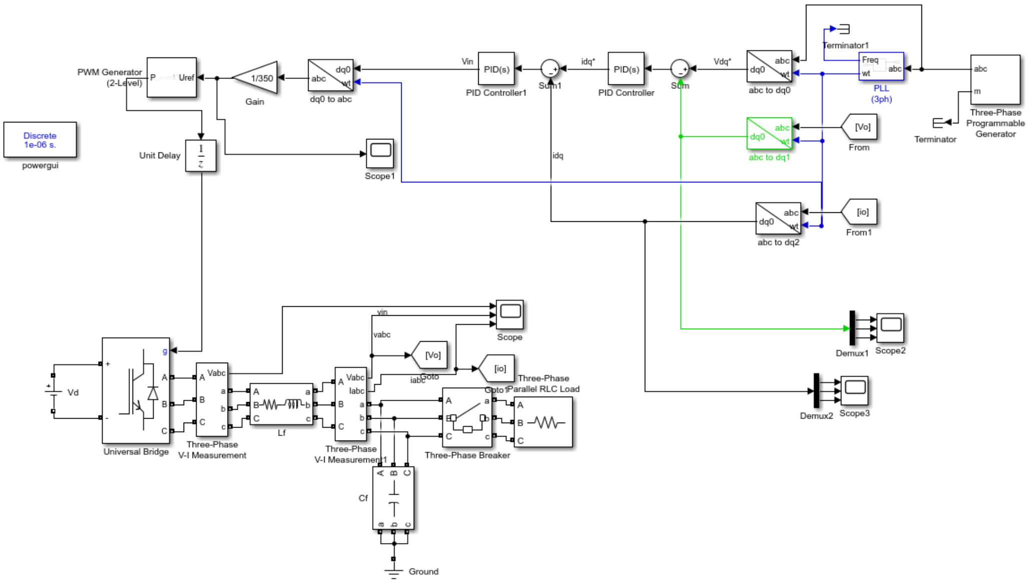


Figure 34 Overall structure of the standalone inverter

For the standalone inverter system, the simulation parameters are presented in the table below.

Table 3 Inverter V/f control simulation parameters

Parameter	**Symbol**	**Value**	**Unit**
Active power	P	30	kW
Input voltage	Vdc	700	V
Grid voltage	Vg	400	V
Inductor	Lf	3	mH
Switching frequency	fs	20	KHz
Frequency	f	50	Hz

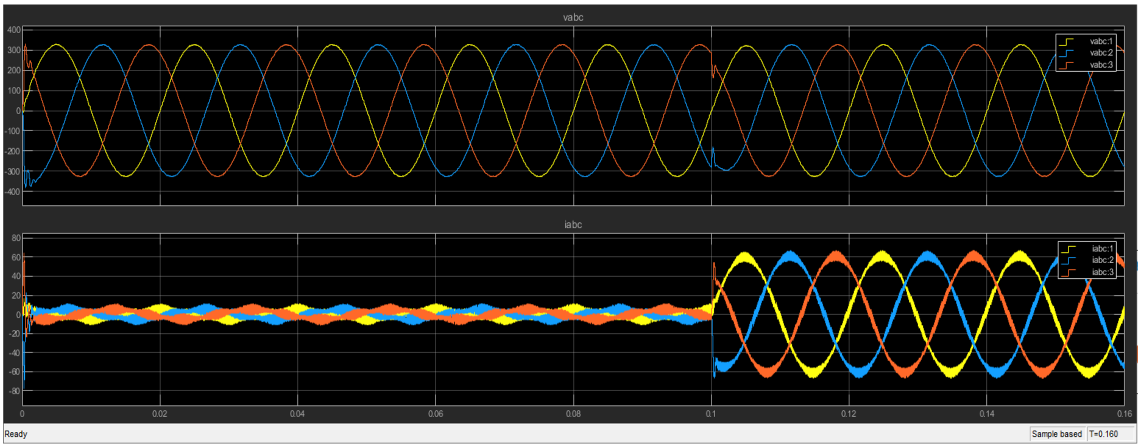


Figure 35 Voltage and current waveforms

Figure 35 shows the voltage and the current outputs which are clean sinusoidal waveforms. The load voltage equal to 400V, and the simulation results show that the output voltage is equal to the peak value (320V). The inverter is supplied with a predetermined frequency of 50Hz, and when we run the system simulation the results show clearly that the frequency is properly controlled and kept constant at 49.99999999Hz as it can be seen in Figure 36.

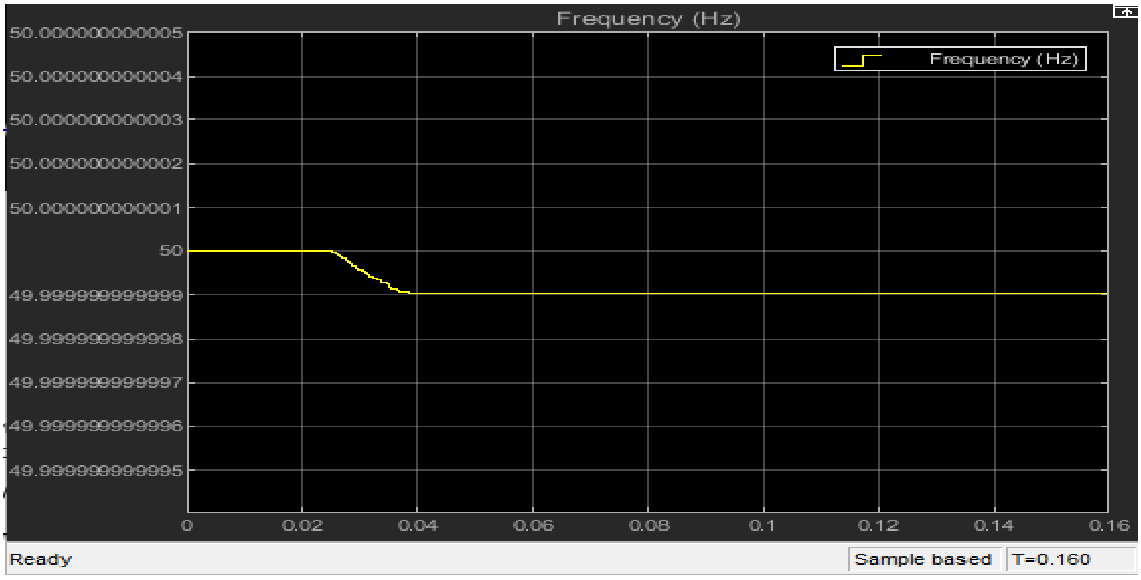


Figure 36 Frequency control

Figure 37 presents the active and reactive powers which vary within the acceptable ranges. At time t =0.1s, the active power is raised and settled around 30kW as it was expected.

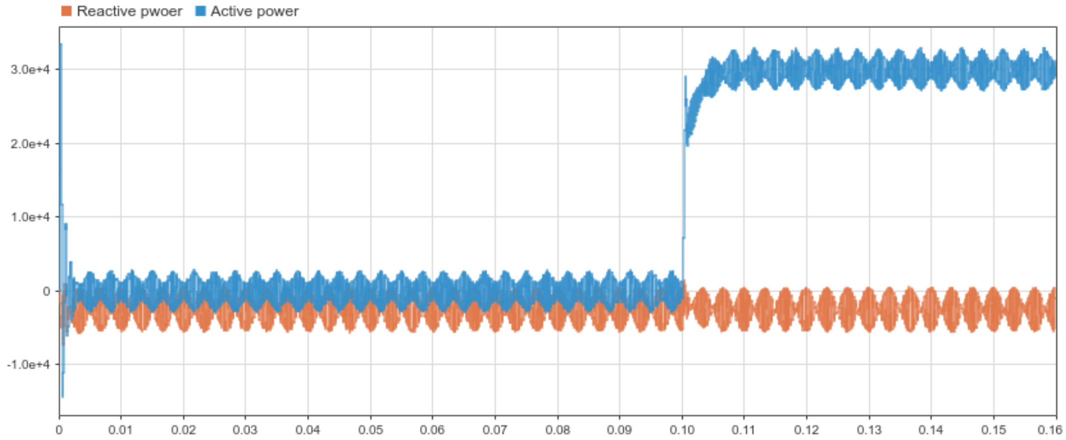


Figure 37 Output active and reactive power

The system active power is 30kW. When the active power is changed for example to 31kW and 29kW which are considered to be within the acceptable ranges, the results show that the voltage and frequency remained constant as predicted and that ensures that this control works fine. Table 4 shows numerical results of the stated example, it shows that when the active and reactive power vary within the acceptable range and the V/f control is in place, the voltage is not affected.

Table 4 Active power Vs voltage in V/f control

Active power P (Kw)	Voltage V (v)
29	320
30	320
31	320

- Droop control

Droop control has shown to be a highly effective method of inverter based microgrid control. It can be implemented either in centralized or decentralized controlled MG. In droop control, the active power is controlled by the frequency droop $(\omega - P)$ characteristic. Similarly, the reactive power variations are associated to the changes in voltage, and the reactive power is controlled by the voltage droop $(V - Q)$ characteristic. Therefore, using the stated droops the reference values of P and Q are generated.

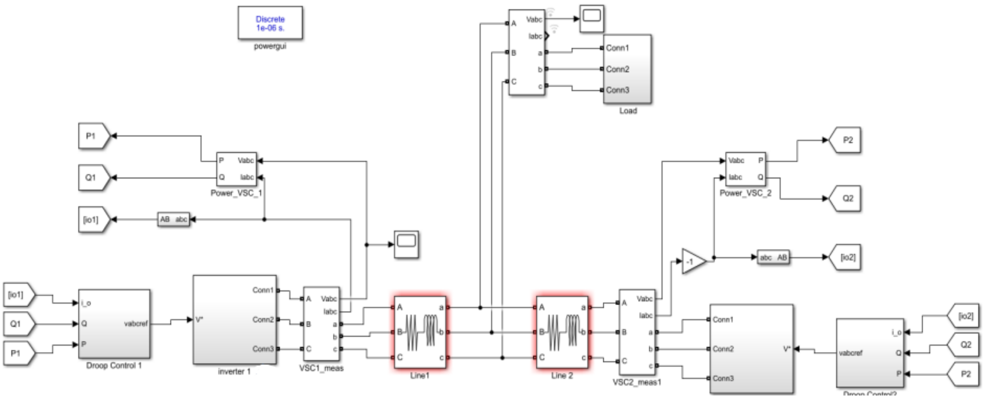


Figure 38 Standalone microgrid with two parallel inverters

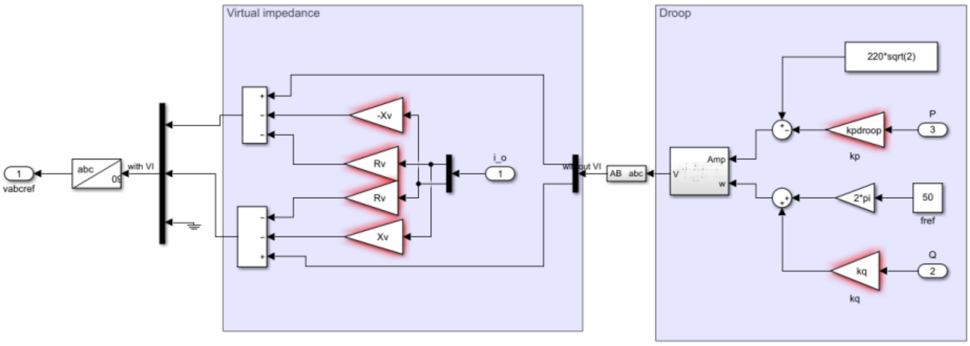


Figure 39 Droop controller

In this control mode, the frequency is measured by the PLL and is compared with the reference value (50Hz or 60Hz). A low pass filter maybe used to filter the frequency deviations and the frequency is multiplied by a gain constant to obtain a droop control. I case of a system with a high ratio of reactance to resistance, the reactive power affects the terminal voltages. Therefore, the reactive power is controlled by Q-v droop. The voltages are measured and compared to the reference values, then the error is filtered by a low pass filter and multiplied by a gain constant to obtain a droop control. However, the output voltages of the voltage regulator determine the needed reactive power to be injected.

7 CONCLUSIONS

When a centralized control is implemented in a microgrid, a single entity is responsible of carrying out the decision-making processes, economic dispatch and unit commitment calculations. In such case, the set points are provided to the DGs by the DSO or MGCC. The centralized control method is considered to be suitable when all actors in the microgrid have common goals. Contrary, in decentralized control scheme, the internal control is performed at each controllable unit in the microgrid. In such case, there should be negotiations among the actors since they mostly have different goals. However, common aspects and calculations such as load forecasting, state estimation and security monitoring can still be managed in a centralized way. Furthermore, both centralized and decentralized control methods depend on four main attributes that affect the control structure complexity, which are the number of nodes (DGs and controllable loads), number of messages to be exchanged, size and structure of the system, and accuracy and optimality.

Some of the advantages of centralized control method are providing a high operational knowledge where the main goals are clearly identified and achieved, providing global optimal solutions, allow easy synchronization of the microgrid to the main grid, and effectively use the real time signals for online operations. The centralized control method presents also a number of drawbacks, they are computationally expensive and time consuming due to the fact that the central controller has to run an optimization problem that considers a large number of DGs, ESSs and loads that make up the microgrid. Another issue is that the central controller requires an extensive communication structure which leads to additional costs. On the other hand, the decentralized control method has significant advantages. It is suitable for fast changing infrastructures and is easily expanded due to its plug and play capabilities. In addition, it provides a high reliability and stability of microgrid. However, disadvantages of the decentralized control method are highlighted. It may be very complex with respect to the multi-ownership and competition between various actors or agents, where everyone is looking to achieve own objectives such as maximization of profits.

Using MATLAB/Simulink, grid-connected and standalone inverters were simulated and different control strategies such as PQ and V/f control have been discussed. These controls have significant effect on balancing the voltage magnitude, maintaining the frequency and power sharing. PQ control is implemented to keep the active and reactive powers constant, while the frequency and the voltage deviate but within the predetermine limits. In this scenario, the active power controller maintains the P output constant and equal to the reference value and the frequency variations remain within the acceptable range. On the other hand, the reactive power controller maintains the Q output constant and equal to the reference value, and the voltage variations are kept within the acceptable range. When V/f control is implemented, the inverter is controlled and supplies to the load with predetermined values of frequency and voltage. Therefore, the voltage and frequency are kept constant while the active and reactive power may vary within acceptable limits. The droop control is a highly effective method of inverter based microgrid control. It can be implemented either in centralized or decentralized controlled MG. In droop control, the active power is controlled by the frequency droop $(\omega - P)$ characteristic. Similarly, the reactive power variations are associated to the changes in voltage, and the reactive power is controlled by the voltage droop $(V - Q)$ characteristic. Some further work is needed for the models to be set up with proper system and controller parameters to achieve stable operation.

To summarize, the integration of DGs in microgrids and power system in general brings the benefits such as reducing the transmission losses, providing better voltage support, improved power quality, and other ancillary services and reducing greenhouse gas emission. However, the high increase penetration of DGs in the distribution network rises many challenges including changes in voltage profile, increased energy prices, and stability and security of the main grid. To overcome those challenges, the modern power system named smart grid requires an advanced high-quality control architecture.

REFERENCES

Alam, M. Ashfaq, S. S. Zaidi and A. Y. Memon (2016). Robust droop control design for a hybrid AC/DC microgrid. *UKACC 11th International Conference on Control (CONTROL)*, 1-6. doi: 10.1109/CONTROL.2016.7737547

Baboli, M. Shahparasti (2014). Energy management and operation modelling of hybrid AC-DC microgrid. *IET Generation Transmission and Distribution*, vol. 8, no. 10, 1700–1711. https://doi.org/10.1049/iet-gtd.2013.0793

Bani-Ahmed, M. Rashidi, A. Nasiri and H. Hosseini (2019). Reliability Analysis of a Decentralized Microgrid Control Architecture. *IEEE Transactions on Smart Grid*, vol. 10, no. 4, 3910-3918, July 2019. doi: 10.1109/TSG.2018.2843527.

Begum, L. Li and J. Zhu (2017). Distributed control techniques for autonomous AC Microgrid-A brief review. *IEEE Region 10 Humanitarian Technology Conference* (R10-HTC), 357-362. doi: 10.1109/R10-HTC.2017.8288974.

Brearley, Belwin J, and R. Raja Prabu (2017). A Review on Issues and Approaches for Microgrid Protection. *Renewable & sustainable energy reviews 67* , 988–997.

Beitollahi, H., & Deconinck, G. (2007, July). Peer-to-peer networks applied to power grid. In Proceedings of the International conference on Risks and Security of Internet and Systems (CRiSIS) (p. 8).

Bevrani Hassan (2017). Microgrid Dynamics and Control: A Solution for Integra tion of Renewable Power, John Wiley & Sons, Incorporated, 2017.

Bidram and A. Davoudi (2012). Hierarchical Structure of Microgrids Control System, in *IEEE Transactions on Smart Grid*, vol.3, no.4,1963-1976. doi: 10.1109/TSG.2012.2197425.

Bouattour, J. W. Simpson-Porco, F. Dörfler and F. Bullo (2013). Further results on dis tributed secondary control in microgrids. *52nd IEEE Conference on Decision and Control*, 2013, 1514-1519. doi: 10.1109/CDC.2013.6760097.

Bracale A, P. Caramia and F. Mottola (2015). A cost minimization strategy for the control of hybrid AC-DC microgrids in industrial systems. *International Conference on Clean Electrical Power (ICCEP)*, 40-47. doi: 10.1109/ICCEP.2015.7177598.

Caramia, G. Carpinelli, F. Mottola and G. Russo (Jun. 2016). An optimal control of dis tributed energy resources to improve the power quality and to reduce energy costs of a hybrid AC–DC microgrid. *Proc. IEEE 16th Int. Conf. Environ. Elect. Eng. (EEEIC)*.

Chandorkar, D. M. Divan and R. Adapa (1993). Control of parallel connected in verters in standalone AC supply systems. *IEEE Transactions on Industry Applications*, vol. 29, no. 1, 136-143. doi: 10.1109/28.195899.

Chen, F. Milano and T. O'Donnell (2019). Assessment of Grid-Feeding Converter Volt age Stability. *IEEE Transactions on Power Systems*, vol. 34, no. 5, 3980-3982. doi: 10.1109/TPWRS.2019.2920516.

Chen, Z. (2012). PI and sliding mode control of a Cuk converter. *IEEE Transactions on Power Electronics*, 27(8), 3695-3703. doi:10.1109/TPEL.2012.2183891.

Chung, W. Liu, D. A. Cartes, E. G. Collins and S. Moon (2010). Control Methods of Inverter-Interfaced Distributed Generators in a Microgrid System. *IEEE Transactions on Industry Applications*, vol. 46, no. 3, 1078-1088. doi: 10.1109/TIA.2010.2044970

Dandachi, N. H., Rawlins, M. J., Alsac, O., Prais, M., & Stott, B. (1996). OPF for reactive pricing studies on the NGC system. *IEEE Transactions on Power Systems*, 11(1), 226-232. doi: 10.1109/59.486099.

Dey and S. Nath (2019). Architecture and Power Converter for Multifrequency Mi crogrid. *Nationaln Power Electronics Conference (NPEC)*,1-6. doi:10.1109/NPEC47332.2019.9034700.

Ding, S. Zhang, F. Gao, X. Cheng and H. Wang (2016). Coordinate control of distrib uted generation and power electronics loads in microgrid. *International Conference on Advanced Mechatronic Systems (ICAMechS)*, 68-72. doi: 10.1109/ICAMechS.2016.7813423.

Dou, Z. Zhang, D. Yue and Y. Zheng (2017). MAS-Based Hierarchical Distributed Coor dinate Control Strategy of Virtual Power Source Voltage in Low-Voltage Microgrid. *IEEE Access*, vol. 5, 11381-11390. doi: 10.1109/ACCESS.2017.2717493.

Dragičević, S. Vazquez and P. Wheeler (2021). Advanced Control Methods for Power

Converters in DG Systems and Microgrids. *IEEE Transactions on Industrial Electronics*, vol. 68, no. 7, 5847-5862. doi: 10.1109/TIE.2020.2994857.

Espina, J. Llanos, C. Burgos-Mellado, R. Cárdenas-Dobson, M. Martínez-Gómez and D. Sáez (2020). Distributed Control Strategies for Microgrids: An Overview. *IEEE Access*, vol. 8, 193412-193448. doi: 10.1109/ACCESS.2020.3032378.

Fahad, A. Goudarzi and J. Xiang (2020). From Grid Feeding to Grid Supporting Con verters: A Constant Power Active Distribution Network Perspective. *IEEE 29th International Symposium on Industrial Electronics (ISIE)*, 862-867. doi: 10.1109/ISIE45063.2020.9152401.

Fahad and E. -R. Ayman (2019). Functions of Microgrid Hierarchal Control Struc ture. *IEEE 7th International Conference on Smart Energy Grid Engineering (SEGE)*, 17-25. doi: 10.1109/SEGE.2019.8859877.

Farhangi Hassan, and Géza Joos (2019). Microgrid Planning and Design : A Concise Guide, John Wiley & Sons, Incorporated, 2019.

Gao, David Wenzhong (2015). Energy Storage for Sustainable Microgrid, Elsevier Science & Technology, 2015.

Guerrero, M. Chandorkar, T. Lee and P. C. Loh (2013). Advanced Control Architec tures for Intelligent Microgrids—Part I: Decentralized and Hierarchical Control. *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, 1254-1262. doi: 10.1109/TIE.2012.2194969.

Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna and M. Castilla (2011). Hierar chical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization. *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, 158-172. doi: 10.1109/TIE.2010.2066534.

Guerrero, J. C. Vasquez, J. Matas, M. Castilla and L. Garcia de Vicuna (2009). Control Strategy for Flexible Microgrid Based on Parallel Line-Interactive UPS Systems. *IEEE Transactions on Industrial Electronics*, vol. 56, no. 3, 726-736. doi: 10.1109/TIE.2008.2009274.

Gupta, S. Doolla and K. Chatterjee (2018). Hybrid AC–DC Microgrid: Systematic Eval uation of Control Strategies. *IEEE Transactions on Smart Grid*, vol. 9, no. 4, 3830-3843. doi: 10.1109/TSG.2017.2727344.

Han, K. Zhang, H. Li, E. A. A. Coelho and J. M. Guerrero (2028). MAS-Based Distributed Coordinated Control and Optimization in Microgrid and Microgrid Clusters: A Comprehensive Overview. *IEEE Transactions on Power Electronics*, vol. 33, no. 8, 6488-6508. doi: 10.1109/TPEL.2017.2761438.

Hatziargyriou Nikos (2014). *Microgrids : Architectures and Control*.2014p25-26. PRINT ISBN 9781118720684 EBOOK ISBN 9781118720653.

Hossain, Md A., Hemanshu R. Pota, Walid Issa, and Md J. Hossain (2017). Overview of AC Microgrid Controls with Inverter-Interfaced Generations. *Energies* 10, no. 9: 1300. https://doi.org/10.3390/en10091300

IEEE Std (2019). IEEE Recommended Practice for the Planning and Design of the Mi crogrid. *IEEE Std 2030.9-2019*, 1-46. doi: 10.1109/IEEESTD.2019.8746836.

IEEE (2014) Recommended Practice and Requirements for Harmonic Control in Electric Power Systems – Redline. *IEEE Std 519-2014 (Revision of IEEE Std 519-1992)* - Redline, vol., no., pp.1-213, 11 June 2014. https://edisciplinas.usp.br/pluginfile.php/1589263/mod_resource/content/1/IEE%20Std%20519-2014.pdf

Jin, J. Wang, K. L. Hai, C. F. Hoong and P. Wang (Oct. 2016). Coordination secondary control for autonomous hybrid AC/DC microgrids with global power sharing operation. *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*. 4066-4071. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8315197

Kaushik and N. M. Pindoriya (2014). Power flow control of hybrid AC-DC microgrid using master-slave technique. *IEEE Conference on Energy Conversion (CENCON*. 389-394. doi: 10.1109/CENCON.2014.6967535.

Laaksonen, H. (2011). *Technical solutions for low-voltage microgrid concept*. University of Vaasa: ISBN 978–952–476–344–8 (nid.) 978–952–476–345–5 (pdf) ISSN 0355–2667, 1799–6961. https://osuva.uwasa.fi/handle/10024/7500

Li, C. Zang, P. Zeng, H. Yu and S. Li (2018). Fully Distributed Hierarchical Control of

Parallel Grid-Supporting Inverters in Islanded AC Microgrids. *IEEE Transactions on Industrial Informatics*, vol. 14, no. 2, 679-690. doi: 10.1109/TII.2017.2749424.

Li, F. Li, Y. Xu, D. T. Rizy and J. D. Kueck (2010). Adaptive Voltage Control With Distrib uted Energy Resources: Algorithm, Theoretical Analysis, Simulation, and Field Test Verification. *IEEE Transactions on Power Systems*, vol. 25, no. 3, 1638-1647. doi: 10.1109/TPWRS.2010.2041015.

Li, J. Hu, Z. Li and J. Lu (2018). Smooth switching control strategy for grid-connected and islanding mode of microgrid based on linear active disturbance rejection controller. *13th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2578-2583. doi: 10.1109/ICIEA.2018.8398146

Lopes, C. L. Moreira and A. G. Madureira (2006). Defining control strategies for MicroGrids islanded operation. *IEEE Transactions on Power Systems*, vol. 21, no. 2, 916-924. doi: 10.1109/TPWRS.2006.873018.

Malatras, A. (2015). State-of-the-art survey on P2P overlay networks in pervasive com puting environments. *Journal of Network and Computer Applications*, 55, 1-23. https://www.sciencedirect.com/science/article/pii/S1084804515000879

Marzal, R. Salas-Puente, R. González-Medina, E. Figueres and G. Garcerá (2017). Peer-to-peer decentralized control structure for real time monitoring and control of microgrids. *IEEE 26th International Symposium on Industrial Electronics (ISIE)*, 140-145. doi: 10.1109/ISIE.2017.8001237.

Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero and J. C. Vasquez (2014). Reactive Power Sharing and Voltage Harmonic Distortion Compensation of Droop Controlled Single Phase Islanded Microgrids. *IEEE Transactions on Smart Grid*, vol. 5, no. 3, 1149-1158. doi: 10.1109/TSG.2013.2291912.

Muyeen (2019). *Variability, Scalability and Stability of Microgrids*, edited by S. M. Muyeen, et al., Institution of Engineering & Technology, 2019.p:20.

Nurunnabi Emon (2020). *Microgrid Protection*. N.p., 2020. Print. https://andor.tuni.fi/permalink/358FIN_TAMPO/1j3mh4m/alma9911209168805973

Olivares (2014). Trends in Microgrid Control. *IEEE Transactions on Smart*

Grid, vol. 5, no. 4, 1905-1919. doi: 10.1109/TSG.2013.2295514.

Padiyar, K. R., and Anil M. Kulkarni (2019). *Dynamics and Control of Electric Transmission and Microgrids*, John Wiley & Sons, Incorporated, 2019. docID=5614126.

Palizban, O., yliopisto, V. & Vaasa, U. o. (2016). *Distributed control strategy for energy storage systems in AC microgrids: Towards a standard solution*. Vaasan yliopisto. https://osuva.uwasa.fi/handle/10024/7800

Pecas Lopes JA, Moreir ACL, Resende FO (2005). Control strategies of microgrids black start and islanded operation. Int J Distri Energy Resour 2005; 1(3):241 À 61.

Radwan and Y. A. I. Mohamed (2017). Networked Control and Power Manage ment of AC/DC Hybrid Microgrids. *IEEE Systems Journal*, vol. 11, no. 3, 1662-1673. doi: 10.1109/JSYST.2014.2337353.

Rocabert, A. Luna, F. Blaabjerg and P. Rodríguez (2012). Control of Power Converters in AC Microgrids. *IEEE Transactions on Power Electronics*, vol. 27, no. 11, 4734-4749. doi: 10.1109/TPEL.2012.2199334.

Rojas and T. Rousan (2017). Microgrid Control Strategy: Derived from Stakeholder Requirements Analysis. *IEEE Power and Energy Magazine*, vol. 15, no. 4, 72-79. doi: 10.1109/MPE.2017.2690520.

Shafiee, J. M. Guerrero and J. C. Vasquez (2014). Distributed Secondary Control for Islanded Microgrids—A Novel Approach. *IEEE Transactions on Power Electronics*, vol. 29, no. 2, 1018-1031. doi: 10.1109/TPEL.2013.2259506.

Shafiee, Č. Stefanović, T. Dragičević, P. Popovski, J. C. Vasquez and J. M. Guerrero (2014). Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids. *IEEE Transactions on Industrial Electronics*, vol. 61, no. 10, 5363-5374. doi: 10.1109/TIE.2013.2293711.

Sharkh, Suleiman M., et al. (2014). *Power Electronic Converters for Microgrids*, John Wiley & Sons, Incorporated, 2014.

Simpson-Porco, Q. Shafiee, F. Dörfler, J. C. Vasquez, J. M. Guerrero and F. Bullo (2015). Secondary Frequency and Voltage Control of Islanded Microgrids via Distributed Averaging. *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, 7025-7038. doi: 10.1109/TIE.2015.2436879.

Teodorescu, Remus (2011). *Grid Converters for Photovoltaic and Wind Power Systems*, John Wiley & Sons, Incorporated, 2011. P: 326. .

Teodorescu, R., Blaabjerg, F., & Liserre, M. (2006). Proportional-resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters. *Journal of Electrical Engineering*, 6(2). https://studylib.net/doc/18153546

Timbus, M. Liserre, R. Teodorescu, P. Rodriguez and F. Blaabjerg (2009). Evaluation of Current Controllers for Distributed Power Generation Systems. *IEEE Transactions on Power Electronics*, vol. 24, no. 3, 654-664. doi: 10.1109/TPEL.2009.2012527.

Tsikalakis and N. D. Hatziargyriou (2011). Centralized control for optimizing microgrids operation. *IEEE Power and Energy Society General Meeting*, 2011, 1-8, doi: 10.1109/PES.2011.6039737.

Variam Kezheke, S. R., yliopisto, V., yksikkö, T. j. i. & Innovations, S. o. T. a. (2018). *Hierarchical control of ac microgrids*. https://osuva.uwasa.fi/handle/10024/9299

Yang Zhou and C. Ngai-Man Ho (2016). A review on Microgrid architectures and control methods. *IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, 3149-3156. doi: 10.1109/IPEMC.2016.7512799.

Zakaria Afshar; Mahmoud Mollayousefi Zadeh; S. M. T Bathaee (2019). Sliding Mode Control of Grid-connected Inverters Using Inverter Output Current. *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)* Electronic ISBN:978-1-7281-0653-3 USB ISBN:978-1-7281-0652-6 Print on Demandb (PoD) ISBN:978-1-7281-0654-0.

Zhong (2013). Robust Droop Controller for Accurate Proportional Load Sharing Among Inverters Operated in Parallel. *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1281-1290. doi: 10.1109/TIE.2011.2146221.