Control of a Microgrid in Islanded Mode

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Abstract

Economic, technological and environmental issues are affecting the electrical power generation and transmission. A microgrid is a new technique that can provide electricity with less impact on the environment and is, at the same time, economically attractive. Basically, the concept of a microgrid is to use small-scale renewable generator sources instead of upgrading the main utility grid. This thesis presents a complete microgrid model and investigates the operational behaviour by using simulation software. The proposed control strategy described in this thesis is based on controlling the generators’ output power to match the required power from the loads. This can be achieved by using the active vs. reactive power droop control method, which will make each generator independently controlled. In other words, the generators’ output will adjust without requiring any data from other microgrid components. The main advantage of this technique is it increases the security and stability of the system by providing a supply of backup energy for the load in case one of the distributed generators shuts down.

If there is no synchronous machine to balance between supply and demand under microgrid disconnected mode, the inverters must take the responsibly of controlling the voltage and frequency. The voltage source control method that uses the P/Q Droop control technique is used in this thesis. The results proved that the P/Q droop control method is able to provide the loads with the required power and at the same time maintain the voltage and frequency within acceptable limits during island operation mode.
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Chapter 1

1.0 Introduction

1.1 Microgrid Definition

A microgrid can be described as a series of small-scale electrical power generators that operate in parallel with the utility grid to supply a number of loads. A microgrid is a low voltage network that connects local generator units with the loads. The local generators are called microsources or distributed generators and they can be either conventional power generators or renewable sources. These generators are normally located near the loads. Microgrid technology provides high-quality electrical power to the local loads. Also, it maintains and sustains the power to the critical loads in case of any faults or disturbance in the main grid. A microgrid can operate either in parallel with the main grid or in a disconnected mode. The disconnected mode (or islanding mode) operates when a disturbance occurs in the main grid, and serves to prevent any interruption in the power supply received by the local loads. When the disturbance no longer exists on the main grid, then the microgrid can be returned to its normal operating mode, which is the grid-connecting mode [6].

A microgrid consists of distributed generators (DGs), loads, distributed storage (DS), interconnection switch and control system. These components will be discussed in the next chapter.

1.2 Thesis Objective

The main aim of this thesis is to investigate a strategy to control microgrids. The approach used in this thesis is that of taking over voltage and frequency control when the microgrid is operating in islanding mode. More generally, this thesis will explore the microgrid concept, such as the purpose of a microgrid, its main components, protection issues and principles of operation and control. Overall, the objectives of this study are summarised in the following points:

- to explore the importance of emerging microgrid technology
- to understand the concept of a microgrid and its main components
- to describe and discuss different configurations of the DG controller
• to design and implement a complete model of a microgrid using Matlab/Simulink software
• to verify the efficiency of the P/Q droop control method in controlling the DG behaviour and maintaining stability in the system

1.3 Thesis Outline

Chapter 2: Provides a brief background to the microgrid concept, including its structure, main components, protection issues and modes of operations.

Chapter 3: Presents the DG control configuration and the hierarchical control of microgrids.

Chapter 4: Discusses the proposed control strategy that will be used in the simulation.

Chapter 5: Shows the tested microgrid structure as well as implementation of the system in simulation software.

Chapter 6: Presents and discusses the simulation results.

Chapter 7: Summarises the main outcomes of the thesis and provides some suggestions for future work.
Chapter 2

2.0 Background

This chapter introduces the concept and the need for microgrids. Also, the main components of a microgrid are described. In addition, this chapter includes a discussion on how a microgrid operates and the issues that need to be considered. A discussion on the protection of a microgrid is presented at the end of the chapter.

2.1 The need of Microgrids

As of yet, most people around the world do not realise the importance and benefits of implementing the microgrids that exist now. In fact, using this technology will definitely improve the reliability and reduce the cost and environmental impacts of the electrical power generation.

Ordinarily, a microgrid operates in parallel with the main grid, but sometimes it can work independently. Should any failures occur in the main grid, then microgrids can provide reliable and high-quality power for the local loads. However, in this situation, the microgrid may only deliver power to the critical loads. In addition, the microgrid improves power quality as well as reliability. A book published by the Institution of Engineering and Technology in the United Kingdom discussed the impacts of microgrids. The writers present many reasons why they believe microgrids can improve power quality. These include decentralisation of supply, better matches of supply and demand, reduction in the impact of large-scale transmission and minimisation of downtimes [7]. Therefore, microgrids can be considered as a reliable technology to provide electricity for local loads.

The growth of electricity demand has increased significantly in the last few years, raising economic issues and becoming an important element in electrical power generation. A microgrid has a positive impact in reducing costs. First of all, a microgrid can reduce the loss in the power transmission lines by locating the distribution generators near the loads. Further, using a microgrid will avoid the extension of the main grid if the demand increased, which is one of the major factors of power supply cost, especially when the affected geography is harsh and comprises mountains, hills, etc.

Obviously, microgrid technology will have less environmental impact than the implementation of a large conventional power generator. This is because the renewable energy sources that are used in microgrids have zero or low emissions. Another benefit of microgrids mentioned in the same article in the previous paragraph is that “Physical proximity of customers with
microsources may help to increase the awareness of customers towards judicious energy usage” [7]. In other words, the close location of microsources to the local loads will increase the awareness of the importance of saving energy.

2.2 Main Components

The five main components of a microgrid consist of the DG, loads, DS, interconnection switch and control system. These components will be briefly described in the next sections. As we can see in the figure below, the main grid is connected to a step-down transformer to provide the same level of voltage as that produced from the distributed generators. In addition, a switch links the utility grid and the microgrid. This interconnection switch is responsible for isolating and reconnecting the microgrid to the utility grid. The diagram below represents a simple microgrid structure.

2.2.1 Distributed Generator (DG)

Distributed generators or microsources are the units that provide power in the microgrid. These are normally placed near the loads. These energy sources can be either conventional or renewable energy units. As stated earlier, distributed generators are normally placed near the
loads, which will obviously minimise the power transmission losses between the generators and the loads in the microgrid. Also, some distributed generators can provide heat energy by recovering its excess power of operation. Thus, the overall efficiency of the system will increase and the operation cost of the generator will decrease.

The main difference between conventional and most renewable distributed generators is that the renewable energy sources are considered as current sources; however, most conventional power generators are voltage sources. In other words, the output voltage can be controlled in conventional generators such as the synchronous and induction generator [11].

### 2.2.1.1 Conventional energy sources

A conventional energy generator can be classified as a dispatchable power unit. The output power of these generators is directly supplied to the grid. This is in contrast to renewable energy sources, which require inverters or rectifier devices to convert the output power into AC to match the grid’s requirement. In conventional generators, as shown in figure 3, the voltage can be determined by controlling the speed of the motor.

### 2.2.1.2 Renewable energy sources

Basically, renewable energy is the energy that comes from renewable sources such as the sun, wind, tide and waves. The renewable energy power units such as solar panels and wind turbines require powered electronic devices to convert the power into AC power to feed into the grid. As was stated in the beginning, we will mainly focus on solar and wind power generation.
Solar panel

A solar panel (also known as a PV array) is a group of photovoltaic cells connected together to generate electricity from the energy in sunlight (see figure 4). A solar panel is normally linked to an inverter because the generated power from the panels is direct current (DC). The PV inverter convert the DC output of the PV array into a utility frequency alternating current (AC). In most applications, the PV is also connected to a battery bank to store the energy excess and restore it when needed. When choosing the type of panel, many issues need to be considered, because there are different types of panels and each one has its own specification and uses.

Wind turbine

![Figure 2 Solar panels pointed at the sun to absorb solar energy [10]](image)

![Figure 3 Wind turbines [10]](image)
A wind turbine is basically a device that converts the kinetic energy from wind into a mechanical power to produce electricity. Besides producing electricity, the mechanical power can be used to drive machinery such as devices for pumping water. The wind turbine is made of two or three blades called the rotor. When the rotor spins by the power of the wind, it produces some energy from the movement, which then will power the generator. The figure below shows how the blades are connected to the gear-box and the generator [14].

![Internal structure of a wind turbine](image)

**2.2.2 Loads**

Two categories of loads are connected to the microgrid. The first category is the critical load. This type of load relates to those customers that require an uninterrupted supply of electricity; for example, hospitals, police stations, banks, etc. These types of loads need a reliable and good quality power supply. The second category consists of the non-critical loads, which are those that can be disconnected when the grid operate in island mode, in order to guarantee sufficient power to the critical loads.

The critical loads in a grid-connected mode are supplied from both the main utility power station and from microsources. However, when the microgrid is operated independently and disconnected from the main grid, the microsources will ensure that power is maintained to the critical loads. In some cases, the microgrid controller will shed the power on the noncritical loads and will supply only the critical loads.
The non-critical loads are the loads that do not require power all the time or are able to function without power for a temporary period. For example houses, clubs, restaurants and libraries are able to survive without electricity. In the case of disconnected mode, the microgrid controller will give priority to the critical loads, and if there is any excess power, only then will it be fed to the non-critical loads.

2.2.3 Distributed Storage (DS)

DS are used to store excess energy in the microgrid. DS is a very important component of the microgrid because it is responsible for providing power in case of a shortfall in supply from the renewable energy units or if the microgrid is operating in islanding mode. DS can be compared to the spinning reserve in main power generators.

Some DS needs a power converter in order to supply electricity to the grid. The installed converter must be a bi-directional converter. The reason for using this type of converter is to supply power to the storage device when there is an excess of energy in the microgrid and to feed the microgrid when there is a shortfall. Basically, the storage devices can be considered as extra or backup generators.

The three main types of DS are batteries, flywheels and capacitor banks. The figures below show the layout of each one. In fact, each type of these devices has its own characteristics and design. For instance, a flywheel is similar to batteries in terms of having a fixed energy capacity. Furthermore, their storage times are rated by the number of minutes of power that can be provided. However, some differences do exist between them. For example, the flywheel output is AC and batteries provide DC, plus the flywheel has a faster response time than batteries. The capacitor has a higher voltage capacity than batteries. However, it stores less energy than either batteries or the flywheel. Furthermore, capacitors are expensive and nowadays no commercial manufacturers produce large-scale capacitor systems [3]. Therefore, batteries and flywheels are more attractive to use as DS in microgrids.
2.2.4 Interconnection switch

An interconnection switch is basically a switch that can be used to disconnect and isolate the microgrid from the main grid in case of any faults or shortage in the main grid. It is also used to reconnect the microgrid to the main grid when the problem no longer exists. In this thesis, we will deal with the Point of Common Coupling (PCC), which is one of the most commonly used interconnection switches in microgrids.

A PCC is a static switch used to isolate and reconnect the microgrid from the main grid. The PCC is a very important element in the microgrid because it protects the local loads from any unexpected or unacceptable power that may damage the loads. For example, a PCC will isolate the microgrid if the frequency in the main grid is not within the acceptable limits. Also, this action will be invoked if there is a fault that will lead to a high current being directed towards the microgrid. Therefore, the coupling PCC is a compulsory element in the microgrid.

2.2.5 Control system

The main responsibility of the control system is to ensure that the voltage and frequency are within the acceptable limits. Many existing strategies can be used to achieve this goal. This thesis will investigate how the primary control can regulate the power in the microgrid for island operation mode.

The correct implementation of the control system has many benefits for the microgrid; such as, reducing emissions by regulating and generating the exact amount of needed power. Besides that, the control system improves the microgrid’s safety when switching between connected
and disconnected modes. Therefore, it is very important to ensure that the control system of the microgrid is operating in the right way.

2.3 Microgrid Operation

The microgrid can operate in either grid-connected or islanding mode. This section will describe both modes and the effects each has on the microgrids. Also included is a discussion of the behaviour of the microgrid at the time of transition between the two operation modes. This section will also highlight some main issues regarding the island mode of operation, as this thesis will focus mainly on the behaviour of a microgrid under the disconnected mode.

2.3.1 Grid-connected mode

A microgrid is normally operated under grid-connected operation mode. In this mode, the microgrid loads receive power from both the utility plant and the microgrid DGs. The microgrid voltage and the frequency in grid-connected mode are regulated by the utility grid voltage and frequency. In fact, DGs are controlled through voltage and frequency regulation for real and reactive power generation using a communication bus. More details and discussion on microgrids under grid-connected mode operation can be found in [12].

2.3.2 Islanding mode

The interconnection switch disconnects the microgrid from the main utility grid in case of any fault or disturbance. In this situation, the microgrid will operate autonomously and will take the responsibility to supply the loads. In addition, the microgrid must ensure that the voltage and frequency are within the acceptable limits.

The microgrid can be switched to operate under island mode in the following two scenarios. The first scenario is the preplanned island operation. If any such events as general faults or maintenance, for example, occur in the utility grid, then the microgrid has to start operating autonomously. The second scenario is the unplanned island operation. This scenario represents the event when there is a blackout due to a disconnection of the main grid, which the microgrid can detect by using appropriate algorithms [12].

DGs are responsible for regulating voltage and frequency in the microgrid. When a microgrid operates in islanding mode, a small deviation may occur from the nominal voltage and frequency. Therefore, DGs are required to maintain the stability of the system by reducing this variation. This can be done by implementing the appropriate control technique on the DG units, which can balance the system [12]. The following section discusses the main issues of microgrid operation under island operation.
Issues with Microgrids in Islanding Mode

Many issues need to be taken into account when a microgrid is operated in disconnected mode. The following points are adopted from an article published by the Institute of Electrical and Electronics Engineers (IEEE), which summarised the main issues of microgrid island mode operation [14].

1) Voltage and Frequency Control

Unlike the grid-connected operation where the voltage and frequency of the microgrid are determined from the utility grid, under the island mode, the voltage and frequency of the microgrid are controlled by adjusting the voltage and frequency of one or more microsources. It is very important to keep the frequency within the acceptable limits. Otherwise, if it falls outside the limits, then the load may temporarily shed.

2) Balance between Supply and Demand

There are three possible operation conditions of power balance between supply and demand in islanding operation mode: supply surplus, supply shortage and equilibrium. In case of supply surplus, the decrease of power generation in microsources can be used to balance the system. However, in case of supply shortage, then the load-shedding technique on the non-critical loads can be used to keep the system in balance [2]. Furthermore, if the microgrid is exchanging power with the main grid before switching to islanding mode, then the secondary control actions should be applied to make sure the initial power is balanced in the microgrid after a sudden fluctuation in supply or demand [14].

3) Power Quality

The power quality of the microgrid should always be in a good condition. The microgrid should take the responsibility to preserve an adequate power quality with a sufficient supply of reactive power in order to minimise voltage sags.

4) DG Issues

There are many issues that relate to the distributed generators in the disconnected mode. For example, some generators have a delayed response when implementing secondary control for voltage and frequency. Moreover, the microgrid has no spinning reserve like the utility grid, but it has DS and DG with built-in battery banks that can be considered to act as a microgrid spinning reserve. The inverter reacts quickly to a fast demand signal and adjusts the power flow levels [14].
5) Communication among Microgrid Components

The implementation of a proper communication infrastructure between microgrid components is a very important issue when selecting the control approach for an islanding microgrid.

6) Planned Microgrid Islanding

Beside the above factors, the microgrid should be prepared for planned islanding. It is very important to include this aspect in the microgrid because it is responsible for maintaining the continuity of power supply during planned outages [14].

2.3.3 Transition between grid-connected and islanded mode

The transition time is when the microgrid switches its operation mode. To provide a high reliability level, the restoration time must be minimised as much as possible. When the microgrid is disconnected from the utility grid, the interconnection switch has to adjust and modify the power reference to match with the nominal value. Moreover, the maximum deviation allowed for the voltage and frequency is 5% and 2% respectively. If the interconnection switch recognises that the fault or disturbance in the utility grid no longer exists, then it will reconnect the microgrid. However, certain issues need to be considered during the restoration process, such as balancing the reactive power, starting sequence and coordination of DGs [16].

2.4 Protection

Microgrid protection is an essential requirement in implementing and maintaining the microgrid operation. The microgrid has to protect its components in both grid-connected and island operation mode against all types of faults.

As was stated in the beginning of this chapter, the interconnection switch or PCC is responsible for isolating and reconnecting the microgrid with the utility grid. Therefore, the PCC has to disconnect the microgrid when any type of fault occurs in the grid. Professor Hassan Nikkhajoei has published many articles discussing the issue of protecting the microgrid, and he stated that “The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open for all faults”[17].

The distributed generator changes its properties significantly when the microgrid switches to island operation. Moreover, the type of the DG needs to be considered as well. For example, induction and synchronous generators have different protection techniques. The output of the DG is often unpredictable, which causes the grid behaviour to change constantly in response to
a fault occurrence. In fact, protection of the DG depends on the state of the main grid and the protection parameters have to be constantly updated. The following points were adopted from Johan [18], who talks about some protection issues related to installing DGs in a microgrid [18].

**Selectivity**

“System protection is selective if only the protection device closest to the fault is triggered to remove or isolate the fault” [18]. In normal operation or even when a fault occurs, if there are no DGs in the network, the power flows in one direction. Therefore, the system can be protected by applying time grading to the overcurrent relays. However, this technique is not applicable when there is a DG in the system, because there is a possibility that one of the DGs will be disconnected when a fault occurs at a neighbouring DG. The DG’s protective relay will contribute to any short circuit current flowing through a fault at a neighbouring DG. In fact, the tripping current of the protective devices must be assigned between maximum current of the load and the minimum fault current. Also, the parameters of the protection devices should be continuously updated because the output power of DGs sometimes becomes irregular.

**Protective Disconnection of Generators**

DGs should be protected against several expected events, such as over and under-voltages, unusual frequencies, harmonic distortions and short-circuit events. The protection mechanism of the DGs has to select a different time delay, which in fact will depend on the location of the fault. In case of faults occurring in the microgrid, the protection devices that are located between the DG and the fault should have the ability to disconnect the DG from the grid. The disconnection should occur very fast, especially when the fault event is located near the DG.

**Microgrid island mode operation**

Sometimes the microgrid needs to isolate the DGs to prevent unintentional islanding. The purpose of such is not just to protect the grid or the DG, but rather for the safety and protection of any individuals who might be seated close to or touching these DGs at that moment. The microgrid operation under disconnected mode should be considered as an alternative option, even though the use of island mode will increase the reliability of microgrids [18].

**Single-Phase Connection**

Some DGs in the microgrid can inject single-phase power into the grid, which will affect the balance of the three-phase electric current. The injection of single-phase power will consequently increase the current in the neutral conductor and stray currents in the earth. This
current should be minimised in order to avoid any overloading and to ensure the safety of individuals [18].
Chapter 3

3.0 Principles of Operation and Control

3.1 DG control configuration

3.1.1 Unit Power Control Configuration (UPC)

The main purpose of this configuration is to control the power injected by the DGs at a desired value [19]. In UPC configuration, the DGs are regulated to provide a constant output power, which means if the microgrid loads are increased at any time, then the utility grid is responsible for supplying the extra demands. As can be seen in Figure 10, the voltage at the connection point and the DG output current are measured in order to calculate the amount of power that needs to be injected into the generator controller.

However, when the microgrid operates in island mode, the droop controller takes over the DG units to balance the power in the microgrid by ensuring that the voltages and the frequencies of the DGs are the same [15]. The droop control method will be discussed in detail in chapter four.

![Figure 6 Unit output power control (UPC) [19]](image-url)

3.1.2 Feeder Flow Control Configuration (FFC)

The purpose of the FFC configuration is to ensure that the active power flow remains constant at the connection point, as shown in Figure 11. This can be done by controlling the output power of the DG. When the load increases during grid-connected mode, the DG supplies and covers the extra demands in the loads, in contrast to UPC, where the main grid is responsible
for that task. Therefore, the output power of the DG will depend on the load. In other words, the supply from the utility grid will remain constant even if the microgrid loads are increased. Consequently, the FFC configuration causes the microgrid to be seen from the utility side as a true dispatchable load. Again, in disconnected operation mode, the droop controller takes the responsibility for controlling the DG [20].

![Figure 7 Feeder Flow Control (FFC) [19]](image)

### 3.1.3 Mixed Control Configuration

Mixed control is based on combining the UPC and FFC configurations together. Basically, some DGs regulate their active power and some others regulate the feeder power flow [20]. Depending on the needs, each microsource will control either the power or feeder flow. The main benefit of using this configuration is to improve the overall efficiency of the system.

### 3.2 Hierarchical Control of Microgrids

A microgrid has some similarity in terms of operation control to the utility grid. Figure 12 shows the main three control levels in a microgrid, which will be explained in the next few paragraphs.
3.2.1 Primary control

The primary control can be considered as the first level in the control system of a microgrid. Basically, the concept of this level is to control the output of each microsource. The primary control, also called decentralised control, normally uses the droop control method. This method is used to emulate physical behaviours of a synchronous machine that make the microgrid more stable [12]. In addition, the droop control can be described as a method that is used to share load between converters. In grid-connected mode, all the microsources must have the same droop function. The droop control method is explained in detail in Chapter four.

3.2.2 Secondary control

As can be seen in figure 12, the secondary control is the second level in the hierarchical control levels in a microgrid. This control level has the responsibility of removing any steady state error that might be produced from the primary control. In other words, the secondary control maintains and improves the power quality in a microgrid. Unlike the primary control, this control needs communication from and to the microsources. The supervisor system (see Figure 13) sends signals to the DGs’ inverters by using low bandwidth communication in order to restore the microgrid voltage to the nominal value. In addition, when the microgrid switches from island to grid-connected mode, the secondary control has the responsibility to synchronise the microgrid voltage and frequency to the utility grid [12].

To maintain the stability within the microgrid, the secondary control reduces the voltage and frequency deviation that has been produced by the primary control. This can be done by
updating the setpoint of the DGs voltages and frequencies to coordinate the microgrid status. To sum up, secondary control is an important factor for preserving a safe and stable operation in the microgrid [21].

### 3.2.3 Tertiary control

Tertiary control has different responsibilities from primary or secondary control. This level of control is more concerned with global issues, such as improving overall power efficiency. The tertiary control regulates and decides the amount of power that can be imported or exported between the microgrid and the utility grid. The principle of operation of the tertiary control is based on adjusting the inverter’s references in the microgrid to ensure optimisation of the power flows.

Importing and exporting energy from the microgrid depends on economic issues concerning whether it is worthwhile to sell or buy power. The decision, which is made by the tertiary control, is based on various economic data and studies [12].

![Tertiary control and the synchronization control loop](image.png)  
*Figure 10 Tertiary control and the synchronization control loop [12]*
3.3 DG Control
A variety of designs can be implemented in order to control the operation of DGs in a microgrid. As this thesis discusses the use of renewable energy sources in the microgrid, therefore, this section will briefly discuss the control strategies that can be used to control the renewable energy sources. These types of generators use inverters to communicate and interface with the grid. Accordingly, to maintain the stability in the system, the inverters of the DGs need to be controlled. The following gives a description of two types of control strategies that may be used to operate the inverter.

3.3.1 PQ inverter control
The PQ inverter control method is based on supplying a given active and reactive power setpoint. This control can only be used when the microgrid is operating under grid-connected mode. The PQ inverter control operates by injecting into the grid the power available at its input. The setpoint of the DGs is predefined in the controller and in most cases is 100% of the available generator output power. The PQ control takes the voltage and frequency of the main grid as a reference to control the DGs’ output. More information about the PQ inverter control can be found in [14, 15, 22].

3.3.2 Voltage source inverter control
Voltage source inverter control (also called VSI) has similar behaviours to a synchronous machine, thus controlling the voltage and frequency of the AC system. Normally, the VSI method is used to control the DGs under island operation mode. Basically, the purpose of VSI is to supply the load with a pre-defined value of voltage and frequency where the real and reactive output power of the VSI is dependent on the load [14]. As has been stated earlier, this thesis will study the behaviour of microgrids by using the VSI method to control the DGs. A discussion and implementation of this control strategy is presented in Chapter 4.
Chapter 4

4.0 Proposed Control strategy

As has been stated in the objectives, this thesis will investigate the behaviour of microgrids under disconnected mode. This chapter proposes a control strategy to support this investigation. In order to do this, it is very important to know the required function and the scenario that will be used on the microgrid.

The control strategy that may be used in a microgrid under island operation mode is different from the one used under grid-connected mode. When the PCC disconnects the microgrid, then the voltage and frequency are no longer controlled by the utility grid. Therefore, the voltage and frequency of the microgrid will need to be controlled internally. One way to do this is by implementing a master controller. The operation principle of this controller is to receive and analyse the data from both the loads and the PCC and then send an order to the DGs to adjust their outputs to meet the amount of power needed by the loads. In fact, there are some disadvantages of using a master controller in a microgrid such as, the system may shut down at any time in case of a breakdown of the master controller. Therefore, the master controller technique has been eliminated [15]. A second type of control strategy, which is going to be used in this thesis, is to assign a controller to each DG. This will cause DGs to be independently controlled. In other words, the output of DGs will be adjusted without requiring any data from other microgrid components. The main advantage of this technique is it increases the security and stability of the system by providing backup energy for the load in case one of the DGs shuts down. The control principle of this technique is similar to the control of a synchronous machine. The inverter is an essential element that needs to be controlled to maintain the stability of the system. The output of the renewable energy units can be controlled from their inverters. The design of this controller is based on determining the voltage and frequency needed by using the “P/Q droop control method.” [12, 20].

4.1 VSI Control Method

If there is no synchronous machine to balance supply and demand, the inverters must take the responsibility of controlling the voltage and frequency. The voltage source control method that uses the P/Q Droop control technique is shown in Figure 15. This method is adopted from [12,15]. The first two blocks, which are labelled as Q and P Calculation, are used to calculate the active and reactive powers injected by the inverter. This measuring stage introduces a delay that corresponds to a decoupling, which is performed through the decoupling transfer
functions. After that, the signals will pass through the P and Q Droop blocks to tune the frequency and voltages respectively. Then these values are used to assign the amount of active and reactive power that needs to be generated by the DG.

![Diagram of DGs control technique](image)

**Figure 11 DGs control technique [15]**

### 4.1.1 P and Q Calculation

The P/Q calculation blocks, which are redrawn in figure 16, use the knowledge of instantaneous values of line-to-line voltages and line currents. These are precisely the quantities that are brought in from the sensing equipment [20]. In both balanced and unbalanced conditions, only two-phase voltages need to be measured and the third one can be calculated because the sum of the three phases is zero. A similar theory can be applied to the line currents; however, it is only valid under the balanced condition.

![Diagram of Active and Reactive Power Calculation Block](image)

**Figure 12 Active and Reactive Power Calculation Block**
The following equations are used to calculate the injected active and reactive powers into the inverter [15]:

\[ P = V_{bc}I_c - V_{ab}I_a \quad (4.1) \]

\[ Q = -\frac{V_{bc}(2I_a + I_b) + V_{ca}(2I_b + I_a)}{\sqrt{3}} \quad (4.2) \]

### 4.1.2 Decoupling

The active and reactive power calculation stage introduces a delay that is represented as a decoupling blocks. The two blocks shown in figure 17 consist of a transfer function and each block has its own required delay time. The decoupling stage holds up the signal received from the P and Q calculation blocks for a specified time.

![Figure 13 Active and Reactive Power Decoupling Block](image)

### 4.1.3 P versus Frequency Droop

The block P versus F Droop in Figure 15 allows DGs to redispatch their output power to match the load requests when the microgrid operates under islanding mode. Ohm’s law demands larger currents from the DGs to increase their measure of output power, and as a result of the droop, the DG units will operate at a frequency slightly less than the nominal frequency of the system, as shown in figure 18 [20]. Also, this block allows the active power to be properly shared across the DGs, depending on each DG’s rated powers.
Figure 18 represents the characteristics of the active power vs. frequency droop for a system that consist of two DGs. $P_{a0}$ and $P_{b0}$ are the setpoints for the active power in grid-connected mode. However, when the microgrid disconnects from the utility grid, the frequency sags to a new value, which in the graph is labelled as $\omega_1$, and the two DGs will generate powers of $P_{a1}$ and $P_{b1}$ respectively. In addition, since the two DGs have the same slope characteristics, this will verify that each DG will share the total active power of the loads, dependent on each DG’s rated power [15]. Clearly, the graph shows that the DGs increase their active power when the frequency decreases. The following equations describe this relationship:

$$\omega_1 = \omega_0 - m_p (P_{1,i} - P_{0,i})$$

$$m_p = -\frac{\Delta \omega}{P_{\text{max},i}}$$  \hspace{1cm} (4.3)

Where:
- $m_p$ = slope of the droop characteristics
- $\omega_1$ = new angular frequency of the DG (when the microgrid switches to island mode)
- $\omega_0$ = angular frequency of the DG (when the microgrid is in grid-connected mode)
- $P_{0}$ = active power supplied by the DG (when the microgrid is in grid-connected mode)
- $P_{1}$ = real power supplied by the unit when the system is in island mode
- $\Delta \omega$ = frequency difference between grid-connected operation and the minimum allowable frequency.
- $P_{\text{max}}$ = maximum active power available from the DG

The block diagram below shows the active power droop. Three inputs are injected in to the control block: the measured and desired active power and the nominal microgrid frequency. The output of this control block is the desired angle of the voltage at the inverter. This angle is used to produce the gate pulses, which are fed into the generator.
4.1.4 Q versus Voltage Droop

The reactive power versus voltage droop method is similar to the active power versus the frequency droop method. This method is used in conventional power systems to assign a specific voltage level at the output voltage sources that are calculated based on the injected amount of reactive power. The main purpose of the voltage droop method is to regulate the inverter with the appropriate voltage level. This method is an important element to ensure the stability of the microgrid during disconnected operation because the voltages at each inverter may vary for different technical reasons, which consequently may lead to an unstable system.

The block below shows the details of operation that occurred in the Q vs. E Droop block in Figure 15.

The inputs of the block diagram are the measured reactive power and the desired voltage value, represented as Q and $E_{\text{req}}$ respectively. The output of this block is determined by the linear characteristics of the droop, as shown in Figure 21. The new value of the desired voltage that must be injected in the generator is $E_o$. 

Imagine there are multiple DGs operating in a microgrid during islanding mode and each inverter has different voltage setpoints. In that case, some of them will inject inductive power and the others will inject capacitive power in order to achieve the desired values. Therefore, it is essential to ensure that all the DGs’ inverters are assigned the same voltage setpoints to avoid the consequences of this situation on the microgrid. This can be done by using reactive power versus the voltage droop method since it has been assumed that there is no communication between the inverters. As can be seen in the figure above, the maximum and minimum operation are defined based on the linear relationship between the reactive power and voltage. Each DGs’ droop is scaled so the maximum reactive power absorbed by the unit corresponds to the maximum allowable operating voltage and the maximum reactive power supplied from the unit corresponds to the minimum allowable operating voltage [15]. The following equation expresses this relationship:

\[ E_o = E_{req} - m_Q Q \]

\[ m_Q = \frac{\Delta E}{Q_{max}} \]  \hspace{1cm} (4.4)

**where:**

- \( E_{req} \) Operating voltage of the unit
- \( E_o \) = nominal voltage
- \( Q_r \) = reactive power injected or absorbed by the unit
- \( m_Q \) = slope of the droop characteristics
- \( \Delta E \) = difference in the voltage between the nominal value and the maximum/minimum value
- \( Q_{max} \) = maximum reactive power available to the DG
From Equation 4.4 it can be seen that if a DG is absorbing reactive power (Q negative), then the operating voltage will be higher than the nominal voltage, and if the DG is supplying reactive power (Q positive), then the operating voltage will be smaller than the nominal voltage.
Chapter 5

5.0 Simulation Platform

5.1 Matlab Simulink

Matlab Simulink is a simulation software used for modelling, testing and analysing a dynamic system. Simulink supports linear and nonlinear systems, which can be modelled in sampled or continuous times. This software package provides a graphical interface, which makes the program easy to use for the non-programming user. The Simulink library contains a range of components that are used to design and test different types of electrical and mathematical systems. The output of the simulated system can be represented as waveforms or numerical data. More information about the use of Simulink can be found in [1].
5.2 Implementation of the Tested Microgrid

For the purpose of the thesis investigation and proposed control strategy, the LV microgrid system shown in figure 22 has been designed and implemented in Simulink. The microgrid system and scenario is adopted from [2] and will be discussed in Chapter 6.

The main utility grid is represented by a 6.6kV distribution network model. The model consists of a power plant, main grid load, distribution lines, interconnection switch and a transformer. The implementation of these elements is described in the next section.

The distributed generator in the proposed system is a wind turbine and the loads are represented as three-phase balanced loads. The generator is in three-phase Y-g configuration. The operating voltage will be 240v with a tolerance of 5% and the system frequency will be
50Hz with a tolerance of 2%. Figure 23 shows the implemented design of the system in Simulink.
5.3 System Modeling

5.3.1 Utility Grid

The figure below represents the utility grid configuration in Simulink. A three-phase source has been used as the utility plant connected to a distribution line, which ends at a static switch. The static switch or PCC is represented as a three-phase breaker with a timer to assign a specific time to disconnect the microgrid from the main utility grid. As can be seen from the figure, the last block is the substation, which corresponds to a step-down transformer.

The PCC will isolate the microgrid when any disturbance occurs in the utility grid. However, in this investigation, a specific time will be chosen to perform the disconnection because it is impossible to implement a scenario where a fault occurs in the utility grid in Simulink. Therefore, the Circuit Breaker Block is used as the PCC, which will give the user the control to connect and disconnect the microgrid at any specific time.

The grid block shown in Figure 24 is a three-phase source, which has a configuration as the swing generation type and the phase to phase RMS voltage is 6.6kV. The utility grid frequency is 50Hz and the transformer is 6.6/0.415kV. More details about the utility grid model are mentioned in Appendix D.

![Utility Grid Model](image)

5.3.2 DG

As was stated in the beginning of this chapter, the system will consist of only one distributed generator. The wind turbine is represented in Simulink as a simple voltage source to avoid the complication of connecting a wind turbine model to the system. However, a wind turbine model is designed in Appendix E to show the behaviour of the wind turbine in Simulink.
Figure 21 Distribution Generator

Figure 25 describes the DG that will be used in the system. The model consists of three Controlled Voltage Source Blocks. These blocks will need an external controller to inject the required amount of voltage that needs to be produced. The DG rated power is 40KVA. It has been assumed that the DG is located near the loads; therefore, the effects of the lines’ impedance on the power received by the loads will be ignored. The droop controller method that has been described in detail in Chapter 4 is used to provide the appropriate amount of power that must be supplied to the system. More information about the controller design and parameters can be found in Appendices B and C.

Figure 22 Implementation of Droop Control in Simulink

5.3.3 Load

A three-phase Series RLC Load Block (see figure 27) has been used as a load. Two of the microgrid loads are considered as critical loads, which means that they must be supplied continuously. The third load is non-critical, which will be disconnected from the microgrid during island operation mode. To perform that function, a circuit breaker has been connected to isolate and reconnect the non-critical load when the microgrid switches its operation mode.
Figure 23 Loads model
Chapter 6

6.0 Simulation Results and Discussion

6.1 Simulation scenario

The test scenario and load parameters are adopted from [2]. Basically, the main objective of this test is to investigate the behaviour of the microgrid during disconnected mode. Also, this test will verify the load-shedding technique, which is used to reduce the demand on DGs in order to maintain the stability of the system.

As can be seen from Figure 23, the main grid is supplying its own load at a rated 27kw and the microgrid is supplying three loads. The first two are critical loads, which must be supplied continuously. The power ratings for the critical loads are 8.5kW and 12.5kW respectively. The third one is a noncritical load, which will be eliminated when the microgrid disconnects from the main grid. This load consumed 8.5kW, which means that the total microgrid load is 29.5kW. The DG is rated at 40KVA. The DG controller design and configuration can be found in [15] and Appendix B.

The microgrid will disconnect from the main grid after 0.5s from the simulation start. It has been assumed that the DG is not able to supply the three loads at the same time without the contribution of the utility grid. Therefore, load shedding will be performed on the non-critical load when the microgrid is operating under island mode. The following figures show the results for the main grid power, DG output power, system frequency, common bus voltage and the demand by the loads.
6.2 Results

Power Generation

From the simulation results, we can observe that the main grid supplies its own load and shares some demand from the microgrid while in grid-connected mode. It supplied 33.5kW, which means it provides the microgrid with 6.5kW. As can be seen from Figure 28, at 0.5s it drops to 27kW, which verifies that the microgrid is operating in island mode.
A similar situation with the DG output power is shown in Figure 29. According to the simulation scenario, the non-critical load will be isolated during island operation, which means that the DG will only need to supply the critical loads. Therefore, the DG generates about 23kw during the connection of the main grid and when the operation switches to island mode, the output generation drops to 21kw, which is equal to the sum of the critical loads demands.

**System frequency and voltage**

The system frequency during grid-connected mode is 51 Hz, which is within the acceptable limits. However, this is not shown in Figure 30 because the system had not reached the steady state. When the island mode operation starts, the DG inverter assumes the responsibility for
maintaining the frequency of the microgrid. The active power vs. the frequency droop method mentioned in Chapter 4 will inject the nominal frequency, which will ensure that the power produced by the DG is the required amount of power.

Moreover, the microgrid voltage in grid-connected mode was nearly 1pu. When the microgrid operate in island mode the voltage drop to 0.97 pu, which confirm that the loads received power with a suitable voltage level.

**Microgrid critical loads demands**

Moreover, the systems maintain the supply to the critical loads even when the utility power cuts off, as shown in Figures 32 and 33. This confirms that the DG is able to provide the necessary power during any unexpected events from the utility grid. The small oscillation on the critical loads power at 0.5s and 1s is due to the snubber circuit in the switch block.
Microgrid non-critical load demand

The non-critical load power is shown in Figure 34. As has been stated earlier, the non-critical load will be isolated from the microgrid when the supply from the main grid stops because it has been assumed that the DG is not able to supply all the loads at the same time. Therefore, after performing the load shedding technique on the non-critical load, the power goes to zero at 0.5s and it will return back to 8.5kw if the main grid supply resumes.
Chapter 7

7.0 Conclusion

This chapter summarises and outlines the main outcomes of this thesis, and also provides some suggestions for future work.

7.1 Thesis conclusion

In conclusion, this thesis investigates the microgrid concept and proposes a control strategy that can operate the microgrid during island operation mode in a proper and reliable way. The first sections of the thesis introduce the microgrid concept and its main components. This section also describes the microgrid operation and the main issues that need to be considered under disconnected mode such as power quality, balance between supply and demands, and voltage and frequency control. Also, protection concerns of the microgrid during both grid-connected and island operation were stated. Moreover, a discussion on the microgrid control operation such as types of control and DG control configuration are included as well. The first few sections are very important and give an idea of the background of the thesis topic, which will definitely help the reader to understand the analysis of the microgrid behaviour.

The control technique is the voltage source inverter control that is based on the P/Q Droop control method. This method basically allows the DG to be self-controlled and does not require any communication from other devices. Also the shedding of the non-critical load during island operation was performed in order to maintain the power to the critical loads. The results proved that the P/Q droop control method is able to provide the loads with the required power and at the same time maintain the voltage and frequency within the acceptable limits.

7.2 Suggestion for future work

The main aim of this thesis is to investigate the behaviour of a microgrid during island operation mode. However, it did not get involved in detail in the dynamic modelling. Rather, it just gives a brief overview of the behaviour of a microgrid and proposes a method that can be employed in order to control the system. There are many suggestions that can help to develop and extend this thesis. For example, the secondary and tertiary control can be implemented in the system to investigate the operation of each control type. Also, a full dynamic modelling of the DG can
be developed, such as verifying the behaviour of the prime movers and the inverters. Besides that, storage devices can be modelled in the system to explore their impact on the microgrid operation. Finally, different types of renewable energy can be used as the DG, for instance, implementing the solar panel model and comparing its performance with the wind turbine model.
8.0 References


9.0 Appendices

9.1 Appendix A (System Parameter)

**Cable inductance and resistance:**

DG: \( S_{base} = 40\text{ kVA} \quad V_{base} = 415\text{V} \)

The DG cable inductance and resistance can be calculated by using the following equation:

\[
S_{base} = \sqrt{3} V_{base} I_{base}
\]

\[
Z_{base} = \frac{V_{base}}{I_{base} \sqrt{3}} = \frac{V_{base}^2}{S_{base}}
\]

The inductance and resistance values chosen to be 0.1pu, therefore the inductance and resistance of the cable of each Controlled Voltage Source Block is:

\[
:\text{ } Z_{base} = \frac{415V^2}{40\text{ kVA}} = 4.3 \, \Omega
\]

\[
L = 0.1 \times \frac{Z_{base}}{3 \times (2\pi f)} = 0.1 \times \frac{4.3}{3 \times (2\pi50)} = 0.456 \, mH
\]

\[
R = 0.1 \times \frac{4.3}{3} = 0.143 \, \Omega
\]
9.2 Appendix B (DG Controller Design)

**DG Controller Parameter**

**Rated power** = 40 kVA  
**Constant time of active power decoupling** = 0.1s  
**Constant time of reactive power decoupling** = 0.2s  
\[ m_p = \frac{\Delta \omega}{P_{\text{max},i}} = \frac{314-300}{40000} = -0.00035 \]  
\[ m_Q = \frac{\Delta E}{Q_{\text{max}}} = \frac{415-240}{40000} = 0.004375 \]  
\[ \omega_0 = 2 \pi f = 2 \pi \times 50 = 314 \text{rad/s} \]  
\[ V_0 = 240V \]

**DG Controller Implementation**

![VSI three phase control model](image)

Figure 31 VSI three phase control model [22]

The figure above describes the voltage source inverter three phase control based on P/Q droop method that used in this thesis. This system has been implemented in Simulink as shown in figure 36. The only change performed in the implementation is the removal of the \( k_{ff} \) loop. This loop corresponds to a phase feed-forward control, which can improve the stability in the controller. However, this removal did not have a big impact on the controller behavior and stability.
Figure 32 Implementation of Droop Control in Simulink
9.3 Appendix C (DG Controller Test)

The purpose of this test is to investigate the behavior of the DG controller. Also this test will verify how the controller will react to the load changes. The system consists of a DG rated at 40kVA and two loads. Load 1 and load 2 power demands are 32kw, 6Kvar and 5kw, 2kVar respectively. The second load is connected to the system via a circuit breaker. The purpose of the breaker is to isolate this load from system at a certain time, which can reduce the total load demands.

As shown in the figure above, the total load demands is 37kW, 8kVAR. The total load demand will decrease to 32kW, 6kVAR after 0.5s of the simulation start. The system frequency and voltage, DG output power and current, and the system load demands are shown in the following figures.
Results:

1- System frequency and voltage

As it seen from figure 38 that the system frequency was increasing rapidly till 0.5s where the total load been reduced. Obviously, the load variation had a noticeable impact on the frequency. At the beginning of the simulation the total active power of the load was almost equal to the maximum active power that the DG can produce, however when the total system loads been reduced the frequency stabilize at 50.5Hz which is within the acceptable limits. In contrast, the voltage level of the system was around 0.96pu and then it settled at 0.976pu when the total reactive power reduced to 6kvar as shown in figure 39.
2- Power Generation

Obviously the DG controller perfectly supplied the load with the required power need as shown in the figures above. Besides DG decreased its output powers when the total load demands of the system has decreased. The yellow and the purple lines correspond to the active and reactive power respectively.
The figure below represents the utility grid configuration in Simulink. A three phase source has been used as the utility plant connected to a distribution lines, which ends at a static switch. The static switch or PCC are represented as a three phase breaker with a timer to assign a specific time for disconnects the microgrid from the main utility grid. As it can be seen from the figure, the last block is the substation, which is corresponded to a Step-down transformer.

**Utility Grid model parameter:**

**Three Phase Source:** Generator Type – Swing  
Phase to Phase rms voltage – 6.6Kv  
Frequency – 50Hz  

**Distribution Lines:** Resistance per unit length (Ohms/Km) – [0.01273 0.3864]  
Line length – 100Km  

**Transformer:** Winding 1 – 6600Vrms  
Winding2 – 415Vrms
9.5 Appendix E (Wind Turbine)

The figure below represents the wind turbine model in Simulink. The reason of not using this model in the thesis test was because it very complicated to connect it with a P/Q droop method controller. The wind turbine model configuration is taken from [5, 15]. The output power of the wind turbine represented in figure 37 is 1.9339 KW. The aim of this test is implement a complete model of a wind turbine in Simulink, which can assist and help any future work on this thesis.

![Wind Turbine model in Simulink](image)

![Wind Turbine output power (W)](image)