ENG470 PROJECT:

CONTROL OF AN ISLANDED MICROGRID

SCHOOL OF ENGINEERING AND INFORMATION TECHNOLOGY

BY

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Declaration of Originality of Research

I certify that the research, sources, and assistance received during the preparation of this thesis has been acknowledged to the best of my knowledge and ability.

Signed: _______________________________

Abstract

This thesis presents a detailed investigative process into the study of the control of an islanded microgrid. This investigation is done through the research and exploration of multiple existing control techniques for the control of a microgrid and then by analysing them to identify the areas where the existing methods can be altered in order to reduce or mitigate common operational issues.

The final goal was to use the gathered information to develop an innovative strategy that may be used to control an islanded microgrid. However, due to various challenges faced over the course of the project – this goal was not achieved.

In light of this, the aim of this thesis was for it to became a research focused development of a body of work that may be useful or potentially serve as a point of reference for future studies in the control of an islanded microgrid.

1. P & PI Controller Regulation & Response Times
2. Natural Load Sharing Amongst Distributed Generators
3. Secondary Frequency-Load Control Mechanisms
4. Controllable Storage Systems
5. Automated Load Shedding in Microgrids
6. Stabilizer Control Strategies

By developing this list of factors and considerations, this thesis project aims to be a useful resource for future studies performed in the topic of islanded microgrid control. The aspiration is that by collating extensive background, theoretical and technical research in this project, the efficiency of those who may want to continue work in this area of study will be improved.

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Chapter One – Project Background

1.0 Introduction

1.1 History of the Microgrid

The majority of the world's current electricity demand is met by electricity that is generated in centralised generation plants, which are typically situated at long distances from their designated loads for economic, environmental, and safety reasons [3]. This centralisation has led to several drawbacks on modern systems such as congestion on existing lines and limits on the expansion of current networks [5]. However, recent years have seen the power sector having to confront the emerging challenges faced by centralised power systems such as low energy efficiencies and increasing loads [1, 6].

In light of these challenges, it is likely that conventional electrical supply methods will need significant upgrades in order to compensate for the projected increases in electricity demands over the coming years [1, 6]. The complication that arises with this problem however, is that a large majority of the world's current electrical network infrastructure is not typically easy to modify due to the large costs and environmental factors involved [3].

Numerous proposals and ideas have been widely discussed to solve this conundrum, one of which is the concept of the microgrid. The figures below summarise this proposed move from traditional distribution systems to distributed generation. The following sections of this thesis will explore some the key features of a microgrid including its operation, control, concepts and issues associated with its functions.

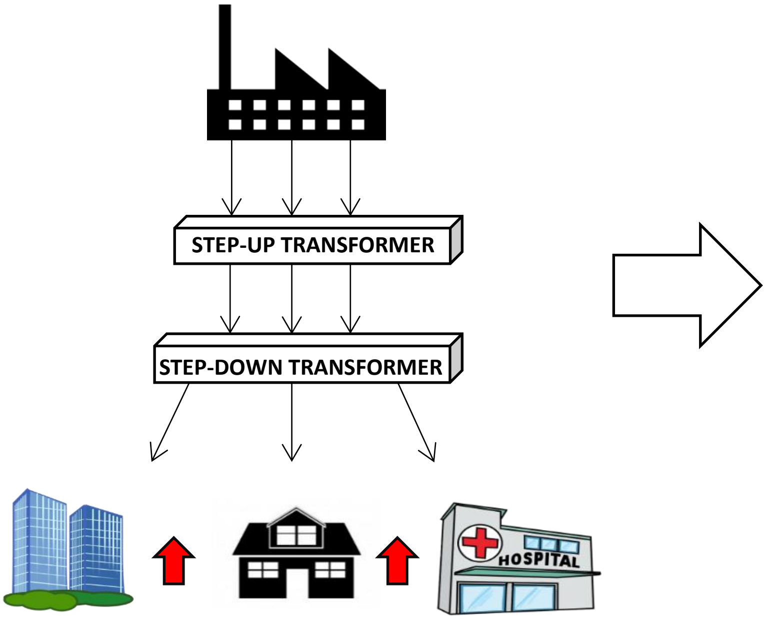


Figure 1.1- 2: Traditional Transmission System

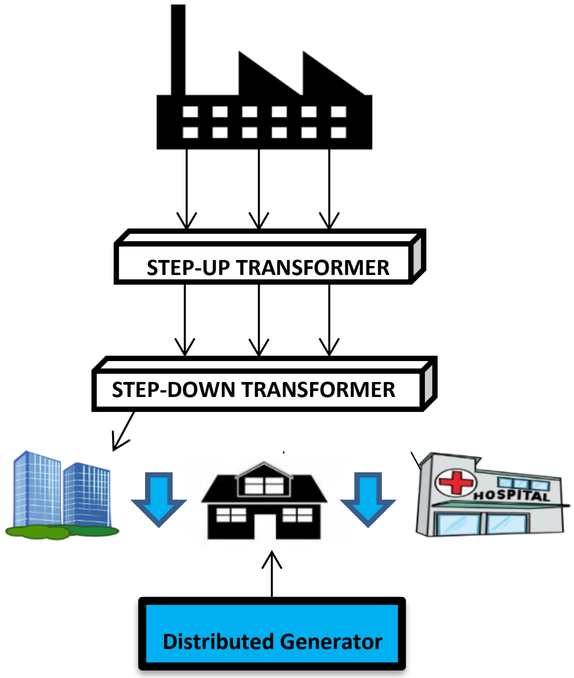


Figure 1.1- 1: Distributed Generation System

1.2 Thesis Objective

This thesis aims to develop an innovative control strategy for the control of an islanded microgrid. This is to be done by firstly exploring multiple existing control techniques and then conducting an investigation to identify the areas where the existing methods can be altered to reduce or mitigate common operational issues. Finally, the gathered information will be utilised in order to develop an innovative strategy that may be used to control the microgrid.

Therefore, the objectives of this thesis can be summarised as follows:

1) Explore existing control methods for an islanded microgrid
2) Identify areas where existing methods can be improved, adjusted or combined to reduce or mitigate issues associated with the operation of an islanded microgrid
3) Develop an innovative control strategy for the control of an islanded microgrid

The following sections of this thesis will highlight the steps taken to develop an innovative control strategy for the control of an islanded microgrid. These steps include gathering some background information on the conception, benefits, operation and control strategies of the microgrid as well as some of the issues that arise with its implementation. At this point, an investigative process shall be conducted to determine how current control strategies can be modified, combined or developed to produce a new, innovative control strategy.

1.3 Thesis Outline

This thesis is to be delivered in 8 chapters which are summarised below:

Chapter One:	Chapter One is associated with providing a brief overview of the microgrid from its historical conception to its modern applications.
Chapter Two:	Chapter Two is concerned with presenting information on the structure of the microgrid and all the purposes of its different components.
Chapter Three:	Chapter Three highlights the operational functions of the microgrid and also highlights the complications associated with the operation of the microgrid, particularly in the islanded mode.
Chapter Four:	Chapter Four then delves into the theoretical concepts behind the control of the microgrid and provides insight into the power flow methods associated with microgrids.
Chapter Five:	Chapter Five presents some of the common methods associated with the control of a microgrid – namely droop and non-droop control methods.
Chapter Six:	Chapter Six then presents an investigation into some of the more common control methods through the presentation of 3 case studies which cover both droop and non-droop strategies alike before presenting the findings associated with each study.
Chapter Seven:	Chapter Seven then summarises the entirety of the project by providing a review of the findings, recommendations for future work and a conclusion.

Chapter Two – Overview of the Microgrid

2.0 Concept of the Microgrid

The function of microgrids is to harness and combine different energy sources in a manner that best caters to the local loads it is designed to supply [5]. The earliest definition of the microgrid was made by the Consortium for Electric Reliability Technology Solutions (CERTS), as a single controllable and independent power system composed of local generator units and storage devices used to supply power to specified loads [1]. Whether these local generators are renewable energy sources such as photovoltaics & wind turbines or conventional diesel generators and energy storage systems, they may all be referred to as distributed energy resources (DER) [5]. Figure 2.1-1 below displays an image of what a possible microgrid configuration might look like.

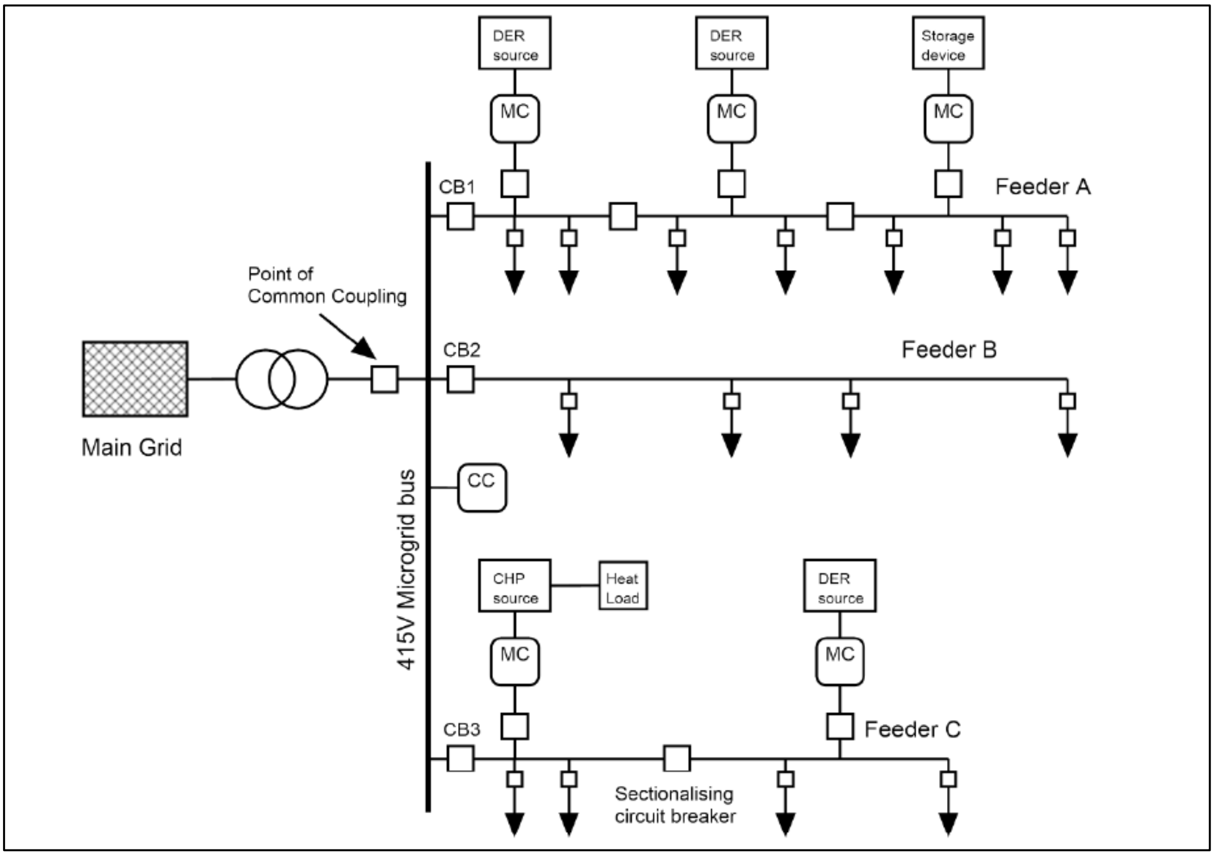


Figure 2.1- 1: Microgrid Network Schematic[31]

2.1 Benefits of the Microgrid

The microgrid offers numerous benefits, but it is its use of decentralised generation that is of significant importance. DER can be integrated into the electrical network and placed closer to the specified loads [3]. DER allows the microgrid to meet the power demand at a closer distance to the local loads as opposed to a centralised system. This makes microgrids an environmentally friendly method of supplying power at distribution levels while improving power quality, reliability, energy utilisation and reducing transmission losses [2]. Distributed energy resources also reduce the need to drastically change the existing electrical power supply infrastructure while increasing their capacity [3]. Some of the benefits that the microgrid offers to both the customers and the utility provider are summarised in the table given below:

Table 2- 1: Benefits of the Microgrid

Category	**Islanded Microgrid Advantages**
Voltage & Frequency	I. Decentralising the electrical supply II. Optimising the matching of electrical demand and supply III. Minimising the effect of any large-scale utility grid blackouts IV. Minimising downtimes during blackouts and maintenance procedures
Operation	I. Improving the voltage profile of the system by increasing reactive support II. Reducing transmission and distribution losses by approximately 3% [8] III. Reducing transmission & distribution feeder congestion IV. Minimises the need for immediate investment to expand existing electrical network infrastructure
Environment	I. They reduce gas & particle emissions because of controlled combustion processes II. They typically utilise renewable energy resources for a large sum of their generation
Marketing	I. May influence a reduction of energy price in power market II. Versatile, as they may be used to provide auxiliary services III. May reduce load on utility grids could reduce electricity generation costs by 10% [8]
Cost	I. Reduction of transmission & distribution losses decreases cost of supply II. Distributed generation reduces need for expansion of existing systems

2.2 Structure of the Microgrid

A microgrid consists of six main components [10]. These key components include the distributed energy resources, energy storage devices, critical and non-critical loads, an interconnection switch, a control system as well as a monitoring and communications system – however this component will not be covered in this thesis project[9]. The following section of the report will provide a detailed description of each of the components of the microgrid that will be discussed in this thesis.

2.2.1 Distributed Generation

The first main component of the microgrid that is to be discussed is distributed generation. Distributed generators are small scale energy sources which supply power to the microgrid and are placed near the loads which they supply [3]. These distributed generators may be conventional generation units such as synchronous generators or non-conventional renewable energy systems such as photovoltaic systems and wind turbines [8].

Distributed generation can offer numerous advantages such as the reduction in transmission costs and demand on the main grid as well as improving the power quality and stability of the loads it supplies. The next section of this report will provide brief descriptions on various forms of distributed generation.

Conventional Sources

Conventional generators, such as synchronous generators may be classified as dispatchable power units [8]. This means that the output of these sources can be directly supplied to the grid as their voltage outputs can be controlled. Due to these factors, dispatchable units are typically considered as voltage sources from an electrical analysis point of view. Figure 2.2-1 below displays an image of a typical industrial synchronous generator.

Figure 2.2- 1: Industrial Synchronous Generator [19]

Renewable Energy Sources

Renewable energy sources may be defined as energy sources which are not depleted after their use [5]. These renewable energy sources, typically solar and wind energy, can be utilised in microgrid systems as distributed generators. The following section of this report will provide a brief description of these forms of distributed energy.

Photovoltaic Panels:

Photovoltaic cells utilise semiconductors to convert the electromagnetic radiation from the sun into electricity and can be connected to form solar panels to generate larger amounts of electricity [20]. Unlike conventional generators however, the energy generated by renewable energy sources is typically is non-dispatchable as it is direct current [8]. Therefore, these renewable energy sources are customarily linked to inverters to adjust the power to the microgrid and utility grid requirements. Figure 2.2-2 below displays a solar panel which may be used as distributed generation in a microgrid.

Figure 2.2- 2: Polycrystalline Photovoltaic Panel [21]

Wind Energy:

Wind turbines utilise the kinetic energy that exists within the movement of the wind to generate electricity [20]. The wind turbine consists of a rotor composed of blades, which rotate when a requisite amount of wind passes along them. This rotation produces mechanical energy, which is then converted to electricity by way of an electrical generator within the wind turbine [20]. Figure 2-3 below displays a wind turbine, which may be used as part of the distributed generation in a microgrid.

Figure 2.2- 3: Commercial Wind Turbine [22]

2.2.2 Distributed Storage

Another key component of a microgrid is distributed storage as it ensures that the microgrid maximises the energy it produces. If the microgrid system is producing more energy than is required, distributed storage devices can store this excess energy [8]. The benefit of this function is that during times when the microgrid or utility grid fails to meet supply demands, the distributed storage devices can act as distributed generators to assist the network in meeting its supply demands by re-supplying the excess energy previously stored.

There are various forms of distributed energy devices, some of which have unique characteristics. Some of these storage devices require power converters to ensure that the power they provide is compliant with the network requirements for example, while others are dispatchable [20]. The most common distributed storage devices are batteries, capacitor banks, and flywheels – each having its definitive characteristics. The following section of this report provides a brief description of each device.

Battery:

The battery stores the electrical energy it collects in the form of chemical energy [25]. The battery has a fixed energy capacity and a storage time that is rated according to the number of minutes of power it can provide. However, because batteries work on a DC basis, a power converter is required to transfer the DC power they produce to AC.

Figure 2.2- 4: Battery Bank Storage [25]

Flywheel:

Flywheel stores energy in a rotational system through a high-speed rotor [24]. Like batteries, the flywheel has a fixed energy capacity whose storage time is rated by the number of minutes of power it can provide. It produces an AC voltage and has a response time that is faster than a battery [23].

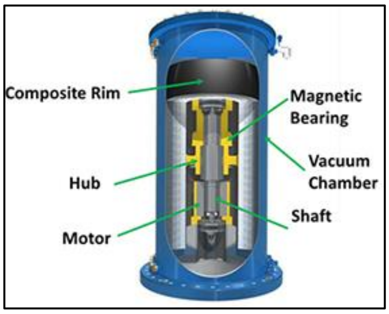


Figure 2.2- 5: Flywheel Storage Device [24]

Capacitor Bank:

Capacitor banks typically have a higher voltage capacity than its counterparts, such as the battery bank for example. However, it tends to store less energy than both the battery bank and flywheel [26]. Additionally, capacitor banks are expensive in comparison to the other devices. Therefore batteries and flywheels are more prevalent.

Figure 2.2- 6: SVC Sapeaçu Capacitor Bank [26]

2.2.3 Loads

The third key component of a microgrid that is to be discussed are the loads. The loads that a microgrid supplies can be separated into two categories; critical and non-critical loads. The critical loads are the loads that require a consistent and uninterrupted supply of power [8]. Typical examples of these critical loads are hospitals, banks and police stations for instance [6]. Non-critical loads are loads that can be disconnected for specified periods of time without necessarily suffering devastating consequences, such as a residential home or a library.

When the microgrid is operating in its grid-connected state, then the loads it is designed to supply receive power from both the microgrid and the utility grid. However, when the microgrid is operating in its islanded state, it is entirely responsible for the supply of its allocated loads [8]. In the case that the microgrid does not have enough energy to supply all of its allocated loads, it designed to prioritise the critical loads by cutting off or reducing supply to the non-critical loads in a process called load shedding.

2.2.4 Interconnection Switch

The fourth key component that is to be discussed is the interconnection switch. An interconnection switch is a device that is used to control the operation of the microgrid in relation to the main grid [5]. When closed, it connects the microgrid to the utility grid, and when open, it isolates the microgrid and ensures it is operating in island mode. A point of common coupling (PCC) is one such interconnection switch, and it will be the interconnection switch of choice for this thesis project.

The importance of an interconnection switch is that it can protect the microgrid from electrical faults and irregularities by isolating it when harmful frequencies are detected for instance [8].

2.2.5 Control System

Finally, the last component of the microgrid is the control system which has the responsibility of ensuring that the microgrid is operating optimally in terms of safety and efficiency. For instance, the control system can ensure that the voltage and frequency levels present in the microgrid are within acceptable margins [4].

A well-implemented control system assists the microgrid to achieve numerous benefits such as reducing the system's carbon emissions, operating at a lower cost than conventional systems, and providing a high level of reliability and quality [4]. The following section of this report will further explore the theory behind the operation of microgrids.

Chapter Three – Functions of the Microgrid

3.0 Operation of the Microgrid

There are three possible states that the microgrid may operate in – the grid connected mode, the islanded mode and the transition period between these two states [1]. The following section of this thesis will provide a brief description and an overview of the key aspects of each of these three operational modes of the microgrid [3].

3.3.1 Grid Connected Mode

In the case that the microgrid is connected to the main utility grid, it is said to be in grid-connected mode. In this state, both the microgrid and the utility grid work in conjunction to supply the loads throughout the distribution network based on demand. In this instance, the microgrid is designed to supply the power it generates back into the main grid any time the grid fails to meet the load demands [12].

Additionally, the regulation of the voltage and frequency of the network is determined and controlled by the utility grid. Therefore, in this instance, there is less risk for the microgrid to fall short in terms of supply adequacy and no need for substantial levels of microgrid control [3]. Figure 3.3-1 below is a schematic of the microgrid's relationship with the utility grid in grid-connected mode.

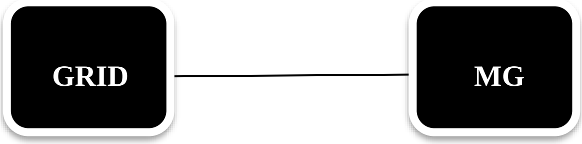


Figure 3.3- 1: Grid-Connected Operation

3.3.2 Islanded Mode

The microgrid can also operate in what is known as the Island mode [12]. In this instance the connection between the microgrid and the main utility grid, typically the point of common coupling (PCC), is open and the microgrid is independent of the utility grid. This scenario may occur due to various reasons such as the loss of the grid supply, emergency situations in the grid network or maintenance procedures.

When this occurs, the microgrid starts operating independently and is responsible for its own power quality and regulation. Therefore, the need for control strategies and methods for the microgrid in its islanded mode is of paramount importance to avoid loss of supply to its critical loads. Figure 3.3-2 below displays the microgrids operation with relation to the grid while in islanded operation.

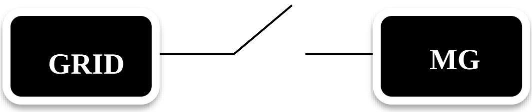


Figure 3.3- 2: Islanded Operation

3.3.3 Transition Period

The third mode of operation for the microgrid is the transition period. This is the period of time it takes for the microgrid to switch its operational modes – from grid-connected to islanded mode and vice-versa [4]. The shorter this transition time for the microgrid is, the higher the reliability of the system [12]. To do this, the interconnection switch should ideally have a controller that can adjust the power levels of the microgrid to match the desired value to ensure optimal performance.

Additionally, the microgrid's active power and frequency levels must operate within an acceptable range of values to ensure stability when it is reconnecting to the utility grid. These values are defined by the network's utility such as Western Power, who recommend a deviation of no more than ± 10% for systems rated above 6 kV and ±6% for systems rated below 6 kV [13]

3.3.4 Operational Issues

As previously stated, when the microgrid is operating in grid-connected mode, the loads receive power from the combination of both the main utility grid as well as the microgrid's DGs while the voltage and frequency are determined by the main utility grid [12].

However, once the microgrid is operating in its islanded state, it responsible for maintaining its own power quality and stability. Hence various issues may arise when the microgrid is operating independently. The table below presents the issues that may arise when a microgrid is operating in Island mode [8]:

Table 3.3- 1: Operational Issues of the Islanded Microgrid

Category	**Islanded Microgrid Issues**
Voltage & Frequency	Voltage & frequency of the microgrid depends on the voltages & frequencies of the distributed generators and loads in the system. These parameters must be controlled and forced to remain within acceptable ranges otherwise load shedding or outages may occur.
Power Quality	Unlike the grid-connected scenario, the microgrid is entirely responsible for the power quality. Therefore, the microgrid should be able to maintain the requisite amount of reactive power in the system to ensure a sufficient supply of power to the local loads.
Supply & Demand	Once the microgrid is in Island mode, the balance of supply and demand can be characterised by one of three scenarios - a shortage of supply, a surplus of supply or an equilibrium. When there is a shortage of supply, there is not enough power in the system to supply all of the loads - therefore load shedding of the non-critical loads has to take place to balance the system. In the case of a surplus of supply, the power generation of DGs will have to be decreased in order to balance the system. In a power equilibrium, no action is required - however, the microgrid must be able to ensure that the system is balanced within an acceptable period of time if the grid is disconnected unexpectedly.
Distributed Generation	Issues that arise with DGs in an islanded microgrid situation is that they tend to have delayed responses in terms of voltage and frequency. This has the added complication that microgrids in Island mode do not have a spinning reserve; therefore, a power storage resource should be involved to ensure a balance is met.
Interconnection	For the microgrid to be able to perform balancing processes accurately and efficiency, there needs to be communication between separate microgrid components.

Chapter Four – Microgrid Control Concepts

4.0 Control of the Microgrid

As has been stated in the previous section of this thesis, various problems may arise during the operation of a microgrid, particularly while it is operating in its island state. This means that in this state, the microgrid is likely to fail in meeting the voltage & frequency stability requirements along with the supply & demand and power quality thresholds. Therefore, to ensure the correct operation of the microgrid in this state – the microgrid should be equipped with control mechanisms that will assist it to be able to meet the desired parameter values. The following section of this thesis will highlight the importance of control in a microgrid as well as some of the control techniques that will be investigated over the course of the project.

4.1 Microgrid Control Theory

A microgrid's power quality, reliability, and security can be drastically improved through the correct implementation of power electronic control strategies and interfaces [32]. The control strategies for microgrids exist in various forms which can be classified as the centralised, decentralised and distributed categories, or any combination of these forms [27].

The centralised control strategies are typically applied to smaller microgrid systems. This is because small-scale microgrid systems require high levels of communication between their distributed generators as they are near one another [32]. In contrast, decentralised control strategies are typically applied to larger microgrid systems that take up bigger geographical domains and have higher voltage levels associated with them. Some of these control strategies will be discussed in the following sections of this report.

4.2 Power Flow Analysis

In summary, for a microgrid to function optimally it requires an effective control strategy to compensate for potential shortfalls which may arise during its operation. However, in order to design an effective control strategy, a method of determining the key variables of a microgrid system is required [29]. One such method is power flow analysis.

Studies on power flow in electric systems have been carried out since the 1960s. These studies have proved useful in the construction and improvement of the world's current power systems as they are essential tools for optimizing the operation of any given power system [32]. The Gauss, Gauss-Seidel, and Newton-Raphson techniques, in particular, are some of the most useful studies on power flow and can be adjusted to cater to microgrid systems in order obtain some of the key parameters such as frequency and voltage.

4.3 Power Flow Analysis in Islanded Microgrids

While power flow analysis methods have proved useful in the design and implementation the large majority of the world's current electrical transmission and distribution systems – they cannot be readily applied to microgrid systems [30].

As was discussed in section 3.0, the microgrid can operate in any one of three modes; grid connected, islanded and transition modes. In the grid connected scenario, the microgrid's voltage and frequency are determined by the main utility grid, which typically keeps these values constant [32]. In the Islanded scenario, however, the microgrid's frequency is not constant. This means that the Y_{bus} matrix of the system, which is dependent of frequency, is also not constant. Therefore, the conventional power flow techniques cannot be readily applied to the microgrid.

Additionally, the power flow techniques conventionally assign the droop bus as either slack, PV or PQ. In this instance, this is also invalid as the active and reactive powers as well as the voltage magnitude and angle of the droop bus in an islanded microgrid are not pre-determined but are dependent on the parameters of the system. This further reinforces the fact that the conventional power flow techniques cannot be applied on an islanded microgrid [29, 32]. Table 4.3-1 below presents a brief comparison and analysis of the current existing power flow analysis methods and their shortfalls as they pertain to microgrids.

Table 4.3- 1: Common Power Flow Analysis Strategies

Power Flow Method	**Rationale**	**Strengths**	**Weaknesses**
Backward/Forward Sweep Methods [33]	A radial network power flow method. Forward sweep is the node voltage calculation from the sending to the feeder end while backward sweep is the branch current and power summation from the far end to the sending end of the feeder [33].	The quadratic equation associated with the sweep methods require only a small number of iterations – which reduces the time to calculate the parameters. This method is also less susceptible to changes in the systems parameters [33].	This type of load flow analysis does not cater to weakly meshed systems or distributed systems with voltage dependent loads or 3-phase distribution systems. It is only applicable to radial systems [33].
Newton-Raphson & Gauss-Siedel Methods [34, 35]	Employs iterative processes which starts off by utilising the voltages at the reference node and loads to develop two iterative solutions of two equations relating to real and reactive powers at the nodes [34].	These processes not only take into account the radial systems – but can be applied to weakly meshed and/or mixed systems [34, 35].	While these methods can apply to radial & weakly meshed systems – they are still not directly applicable to voltage dependent distribution systems and microgrid systems [34, 35].
Numerical Solution Methods [36, 37]	Probalistic load flow processes which involves using different non-linear equations several times to solve a deterministic power flow problem [36, 37].	These processes take into account the weaknesses of the deterministic load flow methods. Therefore weakly meshed and voltage dependent distribution systems are solvable [36, 37].	These processes involve solving large numbers iterative equations which often makes this process impractical depending on the system at hand [37].
Analytical Solution methods [36, 37]	Consists of obtaining density functions of random state variables & line flows through iteration of different input variables [27].	These analytical solutions are applicable to systems with distributed generation & thus are well suited to microgrid systems [36-38].	The density functions obtained are non-linear and therefore need to be linearized -which can lead to errors [36-38].

As can be observed from the existing power flow analysis methods, many possibilities exist to obtain system parameters, but there are drawbacks associated with each method as well. Therefore these considerations must be taken into account when a power flow analysis is performed on an islanded microgrid.

4.4 Primary Control

The control of a microgrid can be characterised into three categories. Primary control is the first level of a microgrid's control system. It is concerned with the controlling the output of each of the distributed generators, which belong to a microgrid as well as allowing for load sharing between the distributed generators [14]. This form of control typically utilises droop control to simulate the physical behaviour of synchronous generators and is dependent on the information gathered during the secondary control stage of the microgrid.

4.5 Secondary Control

The secondary control level of the microgrid is concerned with the determination of the state of the system. It takes into account the properties which available, such and frequency and voltage levels and also includes power flow analysis. Secondary control also consists of the removal of any steady state errors, which might occur because of the primary control of the microgrid [14].

Therefore, secondary control is responsible for the maintenance and improvement of the power quality in a microgrid system. This control system should also be present once the microgrid is operating independently as well as when it is connected to the utility grid and the microgrid voltages and frequency are required to be in synchronisation. This level of control requires a line of communication between the distributed generators, which is to be monitored by a “supervisory control” system, which is responsible for maintaining the optimal function of the system [14].

4.6 Tertiary Control

Finally, the last level of control associated with the microgrid is tertiary control. This level of control is concerned with the overall functionality of the microgrid in relation to the main utility grid it may be connected to [14]. Tertiary control is concerned with regulating the level of power that is to be exported by the microgrid into the utility grid, or vice-versa, to ensure the optimal operation of the overall electrical network. The level of energy which is exchanged between the microgrid and the utility grid depends on external factors such as economic and environmental influences which may depend on the local customers and utilities. Figure 4.6 below summarises the three different levels of microgrid control.

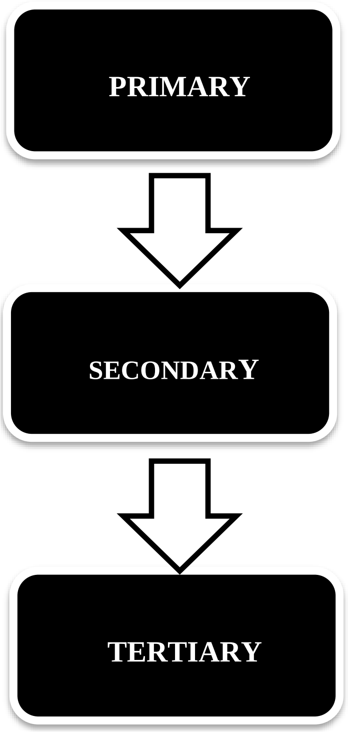


Figure 4.6- 1: Microgrid Hierarchical Control

Chapter Five – Existing Control Methods

5.0 Common Control Strategies

At this point of the project, the theory and processes behind the control of the microgrid have been presented. This section of the report will now present some of the existing methods which are typically used to control the microgrid. Numerous control strategies exist, most of which are droop control strategies and some which are non-droop strategies [27-32]. Droop control methods are the most common form of control when it comes to microgrids, however, and a brief review and comparison of them are displayed below in table 5.1

5.1 Droop Control Methods

The objective of droop control is to manage the real and reactive power demand of the microgrid [29]. The operational principle behind this function of control involves virtually simulating the inertia displayed by synchronous generators. Another manner this could be done is by utilising voltage source converters (VSC) and subtracting the respective average and reactive powers from the frequencies and amplitudes present in the system [27]. The table below presents different forms of droop control, along with the rationale behind the methods, shortfalls and opportunities that may exist with each control method.

Table 5.1- 1: Common Droop Control Methods

Control Method	**Rationale**	**Strengths**	**Weaknesses**
Voltage Droop Control [38]	Involves the adjustment of output voltage frequency & amplitude to implement autonomous power sharing for a microgrid	There is no need to have any form of communication to implement this control method, therefore its implementation is easier to achieve than most [38, 39]	This form of control is not particularly effective for higher voltage microgrid systems with high penetration of renewable energy sources [38].
Frequency & Synchronous Generator Droop Control [40, 43]	Consists of the controller utilising the real power output of the generator to identify the optimal operating frequency for the system	This control method allows the synchronous generator to dampen undesirable fluctuations that arise from changing loads [40]	This control method can only affect frequency and voltage – therefore it can only be implemented in conjunction with an angle droop controller
Angle Droop Control [41]	Utilises a low pass filter to evaluate instantaneous real and reactive power generated in the microgrid to formulate average values which reduce frequency deviation drastically [42]	This control system is able to power share power amongst generators with a much lower deviation in frequency – which improves power quality and stability [41, 42]	This system is doesn't cater as well to systems which do not require power sharing amongst parallel sources
Voltage Source Converter Droop Control [43]	Consists of utilising inverters to control distributed generation units of an islanded microgrid	Active & reactive power control can be used to provide a set-point during grid connection while VSI control can used to measure the powers from terminal outputs	The active & reactive form of control cannot control the frequency of the grid – therefore measurements of active power are unreliable.

These droop control methods are decentralised control methods that are typically suited to high voltage microgrid systems [31].

5.2 Non-Droop Control Methods

While large microgrid systems are typically controlled by droop control methods that have been discussed in section 5.1, centralised control strategies tend to be more suited smaller microgrid systems [27]. This is due to the fact that small-scale microgrid systems tend to require communication between its distributed generators as they are in close proximity to one another [32]. Some of the most common non-droop control methods are presented below in table 5.2-1.

Table 5.2- 1: Non-Droop Control Methods

Control Method	**Rationale**	**Strengths**	**Weaknesses**
Single Master Operation [46]	Voltage source inverter acts as the "master" in islanded operation to create a reference voltage whilst the system is disconnected from utility grid.	The local distributed generators can directly receive required information from the microgrid control system [46].	An allocated secondary load-frequency control is required during islanded operation. It needs to be installed within a controllable DG.
Multi-Master Operation [46]	Involves several inverters acting as voltage source inverters with pre-defined frequency, active power, reactive power and voltage characteristics.	The decentralised nature of method removes the need for potentially costly communications systems between DGs.	An allocated secondary load-frequency control is required during islanded operation. It needs to be installed within a controllable DG.
Secondary Load-Frequency Control [46]	Consists of using storage devices to either inject or absorb active power in order to maintain frequency stability of microgrid system.	This method can control the frequency deviations seen during the islanded operation of a microgrid system using the storage systems.	Storage units are only responsible for load-frequency control during the transient period. Thus this method is dependent on the system's storage capacity.
Allocation of Fixed & Switching Capacitors [47]	Involves allocating fixed & switching capacitors to supply microgrid during all modes of operation to assist in maintaining required reactive power.	This methods improves the utility grid generation to maintain maximum power generation as it doesn't have to compensate for the control of active & reactive power.	Large amounts of potentially costly design & modelling required in order to allocate the capacitors for optimal performance.
Direct Power Control [48]	Consists of utilising 3-phase rectifiers which are interfaced with regenerative loads connected to the utility grid. Involves the use of switching tables [48].	Different switching tables can be used during the rectifier and inverter operational modes to minimise losses and improve efficiency of the method.	While it is a popular method, it is a complex configuration to implement due to the use of co-ordinate transformation blocks.

Chapter Six – Project Investigation

6.0 Microgrid Control Investigation

The aim of this chapter is to visually present and validate some of the ideology behind the microgrid control strategies which were presented in previous sections of this thesis. This is to be done through the presentation of 2 case studies and a PowerWorld simulation which will focus on some of the most popular droop and non-droop control strategies for islanded microgrids, namely voltage droop control, single master operation and P-f Droop Control.

The rationale behind this method of investigation is that by covering existing studies and conducting a simulation which implements some of the most common forms of control for microgrids – a broad and expansive understanding of the key factors concerned with the control of islanded microgrids will be acquired. Additionally, by just analysing one of the control strategies, the scope and time constraints of this thesis project are preserved.

6.1 Case Study I: Ferreira et al.

Aims:

The first case study to be investigated in this presentation is the study of a voltage droop control strategy applied to a DC microgrid in Simulink by Ferreira et al [49]. The aim of the study was to compare the performances of a proportional (P) controller and a proportional-integral (PI) in implementing voltage droop control on a microgrid system.

Method:

This was achieved by implementing the model of a DC microgrid with 3 distributed generators supplying a resistive load using Mathworks' Simulink software. The microgrid's dynamic response was simulated over a period of 500 ms with a step change increase in load being introduced into the system at 250 ms [49].

This simulation was carried out in two situations – the balanced source and unbalanced source scenarios. In the first instance, all of the DGs were tasked with delivering an equal voltage of 200 V each. In the second instance, a simulation was carried out where the DGs were unbalanced and delivered voltages of 250 V, 200 V and 150 V respectively and the different responses of the system were recorded.

Background:

Figure 6.1-1 below displays a schematic diagram of the microgrid system that was modelled in this study.

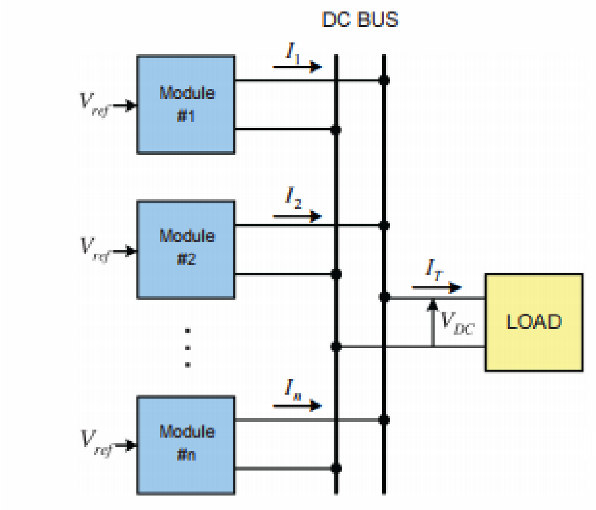


Figure 6.1- 1: DC Microgrid Schematic[49]

Each module represented in the schematic diagram above is composed of a DC source, a static converter along with its associated controller. The composition of each module is represented schematically below in figure 6.1-2.

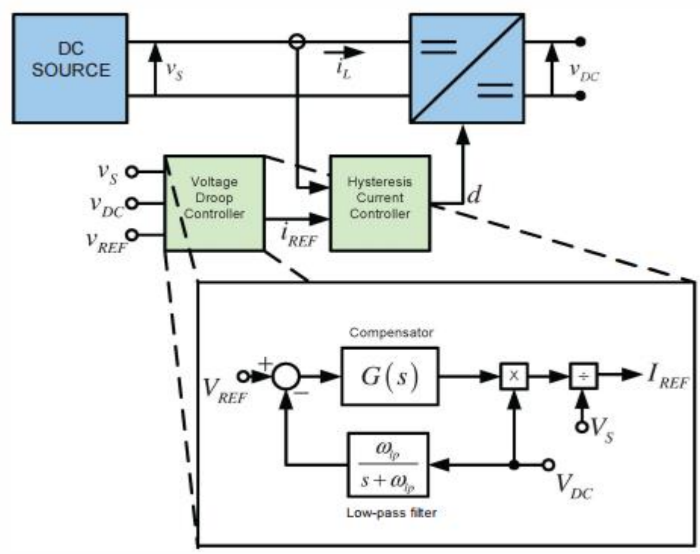


Figure 6.1- 2:Module Composition [49]

In this instance, because the converters have been paralleled, each droop controller naturally imitates the behaviour of an impedance [49]. This means that the higher the level of current that passes through the droop controller, the less voltage that is seen at the converter output. Therefore, by exhibiting impedance like behaviour, load sharing is exhibited naturally in this control strategy without the need of communication infrastructure between the converters – which saves costs and reduces system complexity [49]. This functionality is explained in further detail below;

$$V = I \times Z$$

Where Z represents impedance

<u>Droop Controller Components:</u>

As seen from the schematic diagram of the droop controller, there exists multiple components which need to be defined for the purpose of the simulation. One of the key components associated with the simulation is the low pass filter, which has the purpose of cutting off harmonic frequencies and fast oscillations of the DC bus voltage [49]. It is modelled by the following transfer function;

$$\frac{\omega_{LP}}{s + \omega_{LP}}$$

Where ω_{LP} is the cut-off frequency of the low pass filter

The other component seen in the voltage droop controller schematic is the compensator, which is simply modelled by the following transfer function which will be changed relative to the situation;

$$G(s)$$

The resultant current from the voltage droop control strategy is the reference current for each converter and it is later fed into the current controller. It is represented by the following equation;

$$I_{REF} = \frac{P_{REF}}{V_S}$$

Where V_S is the DC source voltage

P_{REF} is the reference power value for the whole system and is defined by the following equation;

$$P_{REF} = G(s)\left[V_{REF} - \left(\frac{\omega_{LP}}{s + \omega_{LP}}\right)V_{DC}\right]V_{DC}$$

Where V_{DC} is the DC bus voltage at the point of coupling

Additional parameters that are also considered in this simulation are DC bus capacitance and the nominal droop parameters represented by $C_{dc,conv}$ and δ_n.

System Controller Parameters:

The study performed by Ferreira et. al. aimed to produce a performance study of a voltage droop controlled DC microgrid by comparing the capabilities of two controllers to implement voltage droop control on the paralleled converters – the proportional (P) and proportional-integral (PI) controllers.

Both the proportional and proportional-integral controllers may be designed to implement voltage droop control into the DC microgrid system through the appropriate adjustment of their parameters [49]. The table below represents the parameter adjustments made for both of these controllers to be able to implement voltage droop control into the microgrid system.

Table 6.1- 1: Controller Parameters [49]

Controller	**P**	**PI**
Transfer Function	$G(s) = k_p = \frac{1}{R_d}$ *Where k_p is the gain & R_d the source resistance*	$G(s) = k_p\left[1 + \frac{1}{s + T_i}\right]$ *Where T_i is the integral time constant of the controller*
Integral Time Constant	N/A	$T_i = \frac{4}{\omega_{LP}}$

Simulation:

The system which is to be investigated is presented below in figure 6.1-3 as a Simulink model. It involves 3 DGs being fed into a resistive load through their respective modules which include a filter, droop controller and a current controller.

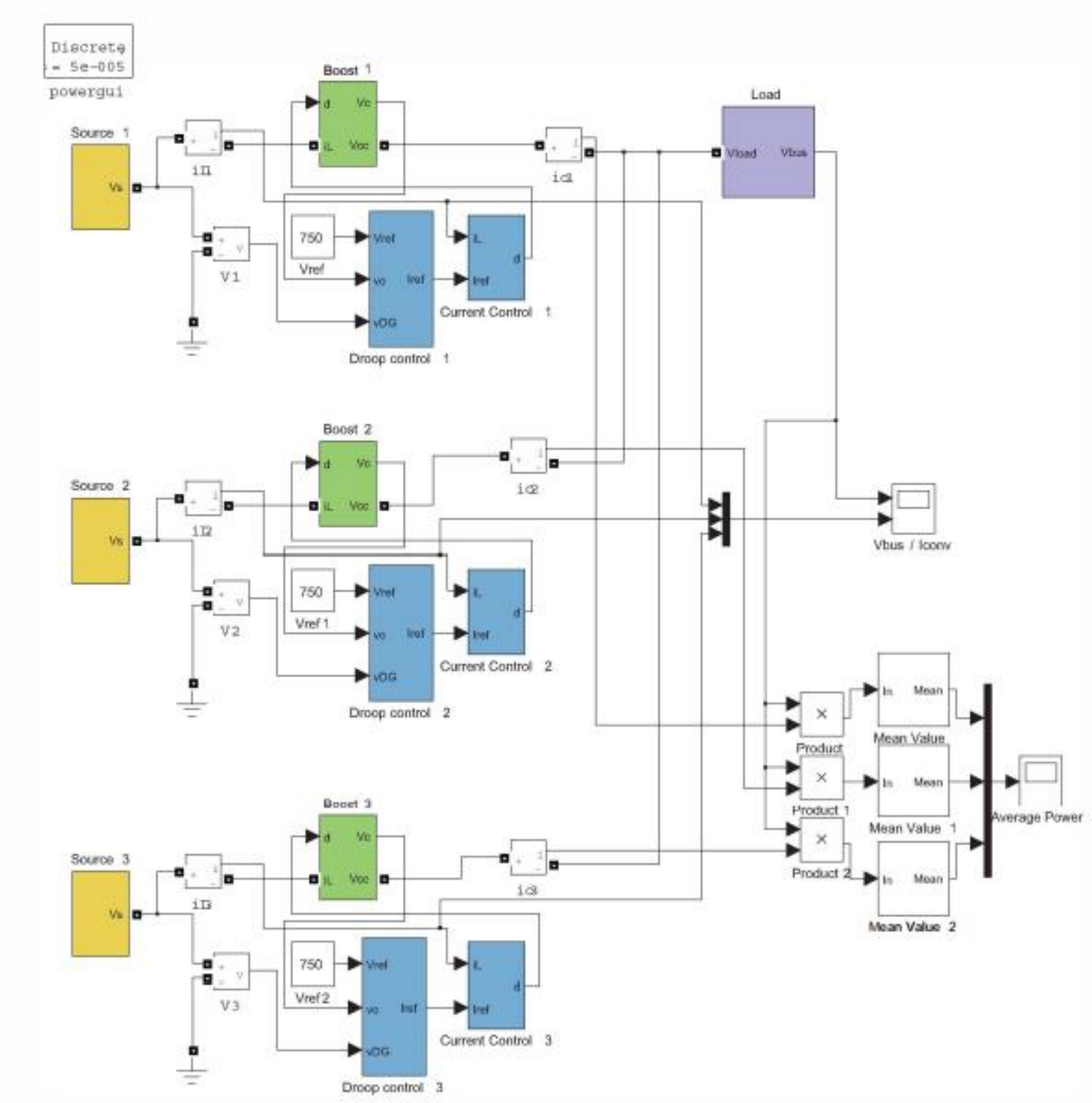


Figure 6.1- 3: Ferreira et al. Simulink DC Microgrid [49]

The input parameters associated with the for the microgrid network are shown below in. These stay constant throughout the whole investigation process.

Table 6.1- 2: Ferreira et al. DC Microgrid Input Parameters [49]

Parameter	Value	Unit
R_d	1.34	Ω
δ_n	5	%
ω_{LP}	100π	rad/s
$C_{dc,conv}$	17	mF
V_{REF}	750	V
k_p	0.75	W/V^2
T_i	12.73	ms

Investigation:

The investigative process carried out on the system was designed to assess the ability of two separate controllers, proportional (P) and proportional-integral (PI), to maintain the stable operation of the DC microgrid system after experiencing a disturbance in its operation by way of a step change increase in load over a 500ms period.

Case I:

Two cases were investigated in this analysis, the first of which involved a balanced supply situation. All 3 distributed generators were delivering equal voltages of 200 V and the system load was increased from 20 kW to 30 kW at 250 ms, which is halfway during the simulation period. The results of this test are displayed below as a comparison of the P and PI controllers.

Firstly, the ability of the two controllers to hold the reference voltage of 750 V over the 500 ms period at the DC bus was assessed. Figure 6.1-4 below displays the graphical performance of the two controllers, with the P controller in black, and the PI controller in green.

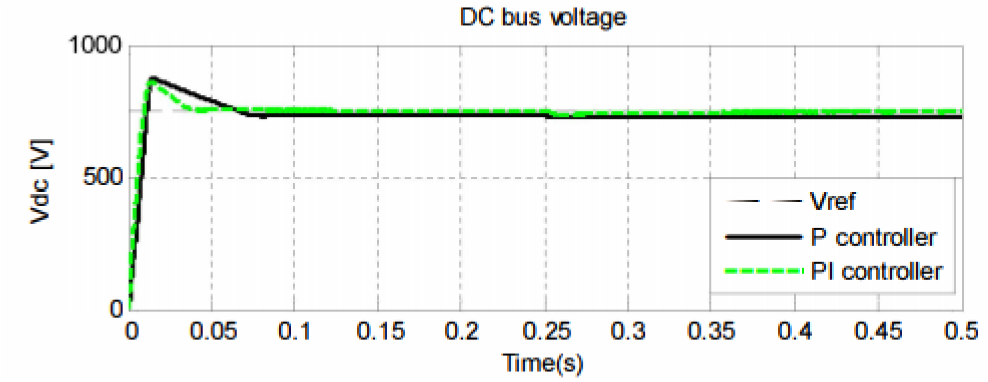


Figure 6.1- 4: P vs. PI Controller Performance Comparison – DC Bus [49]

It is clear to see from the graph that both controllers were able to reach steady state values within 75 ms initially before reacting accordingly after the change in load. However, with closer inspection, it is clear to see that the P controller exhibited a faster response time as evidenced in figure 6.1-5 below – which is a close up version of the response of the two controllers;

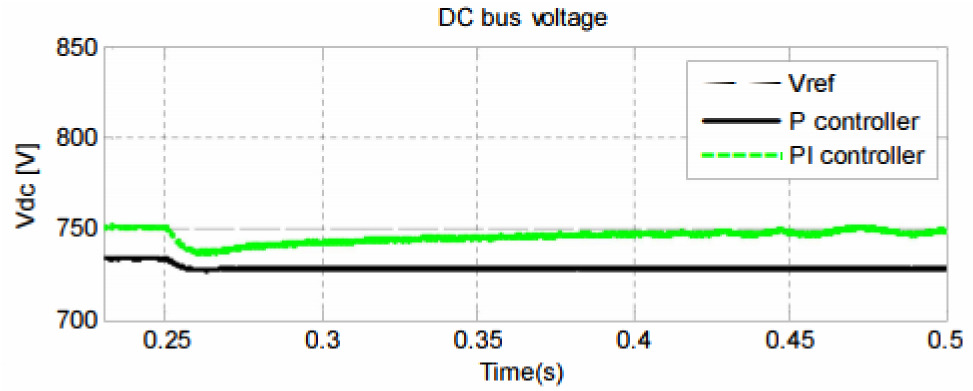


Figure 6.1- 5: P vs. PI Controller Performance Comparison Close Up- DC Bus [49]

It is evident that whilst the P controller was quicker to settle on its steady state value than the PI controller, it exhibited worse voltage regulation. It settled on 740 V before the change in load before settling on 730 V after the change in load – which represents a regulation accuracy of 98.67% and 97.33% respectively. The PI controller in comparison, despite a slower response, exhibits perfect voltage regulation once it reaches steady state. In terms of the average power delivered to the load, the same characteristics are prevalent in the graph shown below in figure 6.1-6.

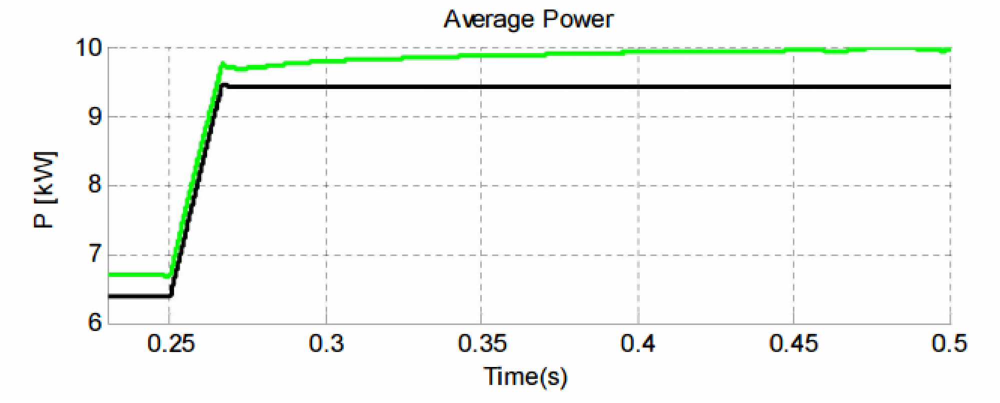


Figure 6.1- 6: P vs. PI Controller Comparison – Balanced Supply [49]

From the graph above, it is once again clear to see that the P controller has a faster transient response time than the PI controller. However, the PI controller has the ability to cancel steady state errors caused by the implementation of the voltage droop control and therefore exhibits better voltage regulation once it reaches steady state.

Case II:

The second case focuses on an unbalanced situation. The 3 distributed generators are set at different voltage levels of 250, 200 and 150 Volts respectively. This simulation better resembles a real world situation as the outputs of the DGs cannot be expected to be balanced at all times since they can vary from photovoltaics, fuel cells and diesel generators.

The same step change increase in load from 20 kW to 30 kW at 250 ms, and the results of this simulation are displayed below as a comparison of the P and PI controllers in figure 6.1-7.

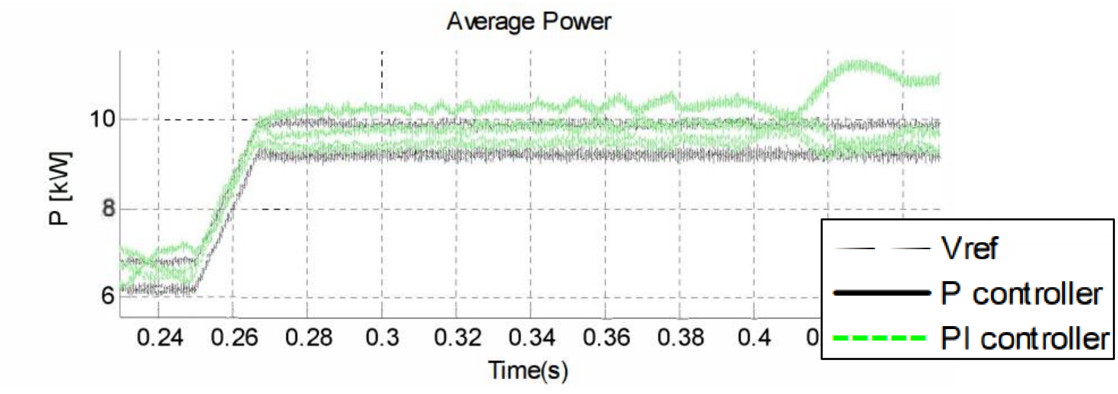


Figure 6.1- 7: P vs. PI Controller Comparison – Unbalanced supply [49]

In this situation, it is clear that the whilst the PI controller has the advantage of removing steady state errors on average, it causes an oscillatory behaviour in the average power delivered to the load [49]. The PI controller is exhibiting a lesser capability to regulate the voltage, but offers a faster response time that ensures a greater level of stability in unbalanced situations.

Findings:

This case study gives a deeper insight into the importance of controllers in implementing droop control methods, particularly the proportional and proportional-integral controllers. In addition to this, this study also gave an insight into the importance of load sharing amongst DGs.

The advantage of having paralleled generators means that load sharing can be achieved naturally without the aid of additional control infrastructure and devices. This reduces the simplicity of the system as well as the possible costs which could be incurred with implementing additional infrastructure.

Table 6.1-3 below summarises and compares the benefits and drawbacks of the two controllers, across the various categories which have been investigated in this case study. Depending on what a system design deems as important, it can be concluded that a proportional only controller is a suitable controller to use over the PI controller as it ensures a fast response time which doesn’t oscillate in unbalanced situations despite a poorer level of voltage regulation.

Table 6.1- 3: P vs. PI Controller Performance Comparison

Controller	**P**	**PI**
Fast Response time	✓	✗
Voltage Droop Implementation	✓	✓
Voltage & Power regulation	✗	✓
Load Sharing Capability	✓	✓
Unbalanced Supply Stability	✓	✗

6.2 Case Study II: Lopes et al.

Aims:

The second case study to be considered in this thesis project is the feasibility study of control strategies to be adopted for the operation of an islanded microgrid by Lopes et al. This study focuses on the performances non-droop control methods implemented in Simulink, including the single master operation (SMO) strategy, which will be investigated in detail In this thesis project.

Method:

This was achieved by performing a simulation of a microgrid system as it is transitioning from the grid-connected operation into the islanded operation. This is done to simulate a situation where a disconnection from the main grid has been forced by the occurrence of a fault or intentionally performed in the case of a planned servicing procedure[46].

The performance of a single master operation control strategy which is imposed on the microgrid system will be analysed in order to gain a deeper insight into the functionality of non-droop control strategies in microgrids.

Background:

The microgrid which is modelled in this study is derived from the system developed within the EU R&D Microgrid Project [46] and is presented below in figure 6.2-1. The microgrid consists of loads, both controllable and non-controllable DGs, storage devices as well as a microgrid central controller.

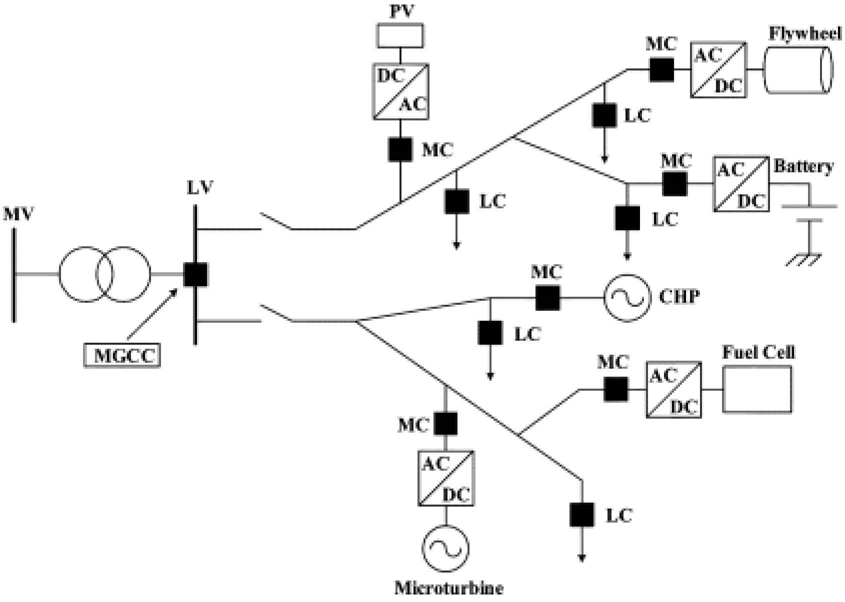


Figure 6.2- 1: Lopes el al. Microgrid [46]

Single Master Operation (SMO) control:

This system and its various components are to be modelled using the Simulink software. The distributed generators to be modelled include fuel cells, wind turbines, photovoltaic arrays and storage devices. The fact that the single master operation method is to be imposed on this microgrid system means that inverters will be involved in the design.

Figure 6.2-2 below displays the schematic diagram of the single master operation implementation – whereby the inverter acts as a voltage reference for the microgrid system after it has been disconnected from the utility grid. The local DGs within the microgrid system receive this information via the central controller and react accordingly [46].

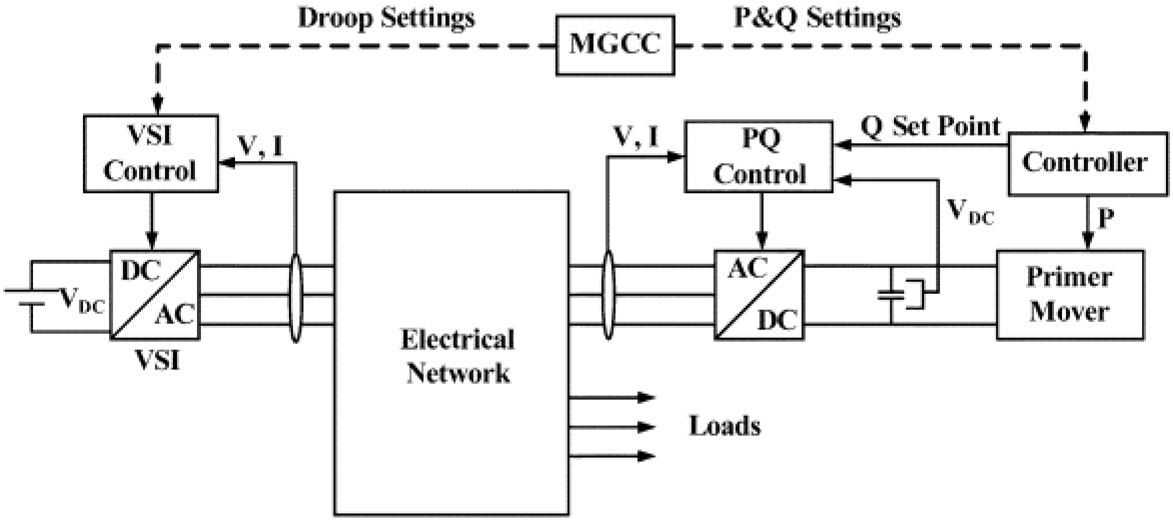


Figure 6.2- 2: Schematic Diagram of Single Master Operation strategy[46]

Voltage Source Inverter (VSI) control:

As was mentioned above, the implementation of the single master operation strategy involves the use of an inverter acting as a point of reference, or master, for the distributed generators in the microgrid network [46]. This requires the inverter to be also under a form of control for it to be able to function in such a manner. The control strategy used for the inverter in this study is the voltage source inverter (VSI) method.

The VSI control method consists of the inverter emulating the behaviour of a synchronous machine in the sense that it is controlled to feed the load with pre-defined values of voltage and frequency, according to the following equations and depending on the load [46].

$$\omega = \omega_o - (k_p \times P)$$

$$V = V_o - (k_q \times Q)$$

Where ω_o *&* V_o *,* P *&* Q*,* k_p *&* k_q *are idle values of frequency & voltage, inverter active & reactive powers, droop slopes respectively*

The VSI control method may be summarised as presented below in figure 6.2-3 below;

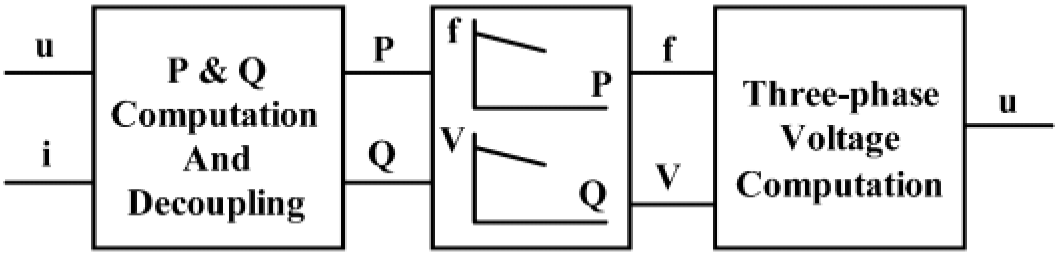


Figure 6.2- 3: Schematic diagram of VSI operation [46]

Secondary Load-Frequency Control:

As was discovered in the previous section of this investigation, the VSI active power output is dependent on the frequency deviation experienced in the microgrid system. As we saw from the previous case study, these frequency deviations are caused by the use of proportional only droop controllers. This becomes an issue when there are energy storage elements present in the microgrid network, as they would continuously inject or absorb energy from the system whenever a frequency deviation away from 0 is seen [46].

In order to overcome this issue, a secondary control method is implemented to assist the system to restore frequency to a nominal value after a disturbance. Centralized secondary control implemented by the microgrid central controller (MGCC) implements the use of a PI controller to eliminate the steady state offset in comparison with a reference voltage. Figure 6.2-4 below presents a schematic diagram of this operation;

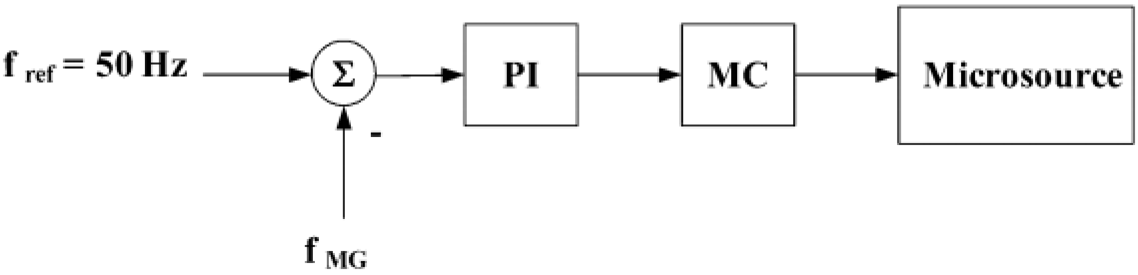


Figure 6.2- 4: Schematic Diagram of Secondary Load-Frequency Operation [46]

Simulation:

The microgrid to be is to be investigated is presented below in figure 6.2-5 as a Simulink model. It is based on a MG system designed by NTUA for research and development purposes. It consists of numerous DGs, loads and storage devices which are all working with reference to the VSI inverter.

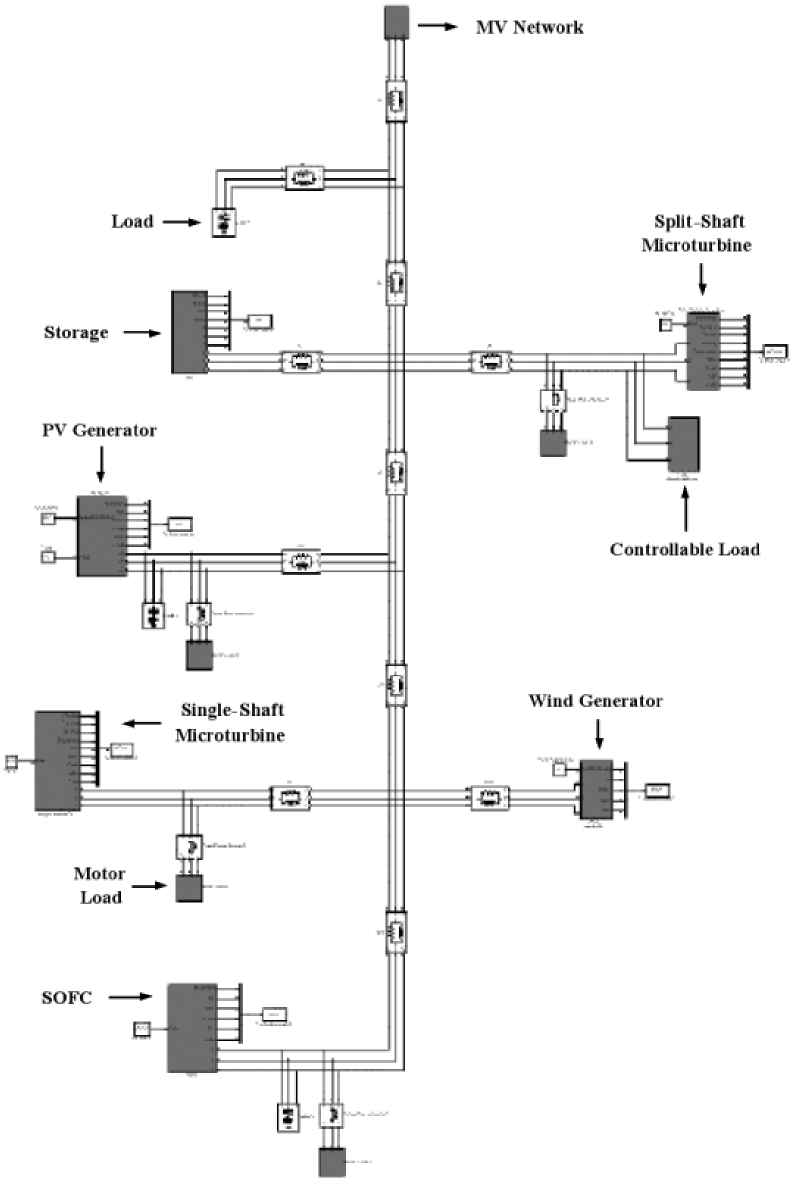


Figure 6.2- 5: Lopes et al. Microgrid Implementation in Simulink

Investigation:

An investigative process into the dynamic behaviour of the microgrid under single master operation and secondary load-frequency control is carried out by simulating the microgrid over a period of 180 s where it is initially grid-connected and is disconnected after 10 s. The parameters concerned with the simulation are displayed below in table 6.2-1.

Table 6.2- 1:Case Study II Simulation Parameters [46]

Parameter	Value	Unit
Local Load	80	kW
Constant Impedance Percentage	65	%
Motor Impedance Percentage	35	%
Fault Occurrence	10	s
MG Islanding	10.1	s

Figure 6.2-6 below displays the frequency seen by the microgrid system over the length of the simulation. Initially it was equal to the grid connected frequency of 50 Hz, but after the microgrid enters islanding mode – we can notice a significant dip at 10 s to 49.5 Hz.

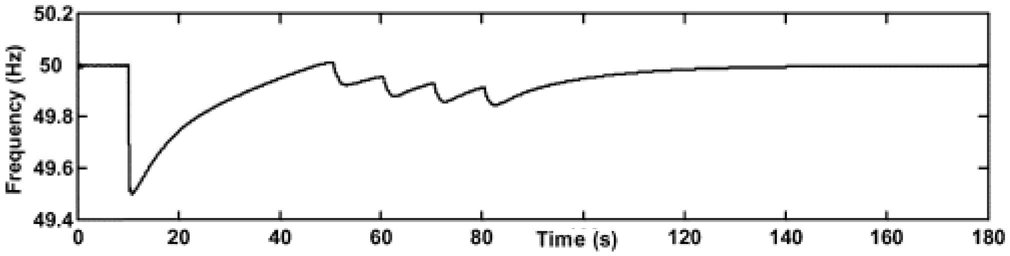


Figure 6.2- 6: Lopes et al. Simulink Microgrid Frequency Response [46]

As discussed earlier, this initial dip in frequency means that the system is not capable of supplying all of its loads in this period of time – therefore the microgrid immediately sheds a majority of its load, starting with the non-critical loads as well as the controllable loads [46].

However, as time goes on we see the effect of secondary load-frequency control begin to take shape as the frequency of the system begins to rise steadily. As this occurs, some of the uncritical and controllable loads which were initially disconnected begin to come back into the picture and take their toll on the frequency curve as is characterised by the jagged nature of the curve from 40 s to 80 s.

Eventually it can be observed that the single master operation is able to restore stable steady state operation into the system as is characterised by the curves in figures 6.2-7 and 6.2-8 below which highlight the behaviour of the VSI and the distributed generators;

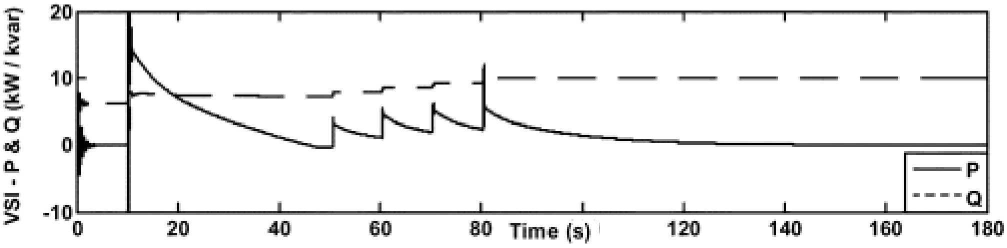


Figure 6.2- 7: Lopes et al. Simulink Microgrid VSI Response [46]

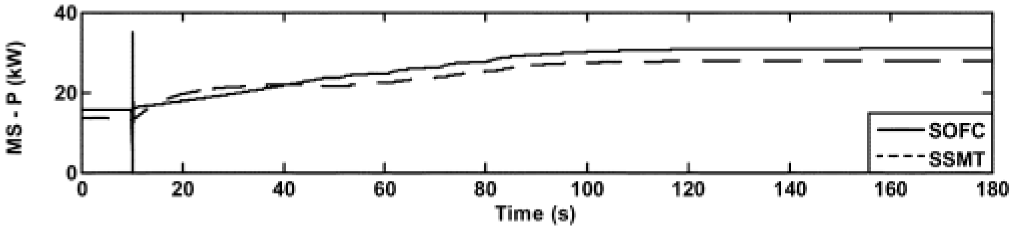


Figure 6.2- 8: Lopes et al. Simulink Microgrid VSI Response [46]

Findings:

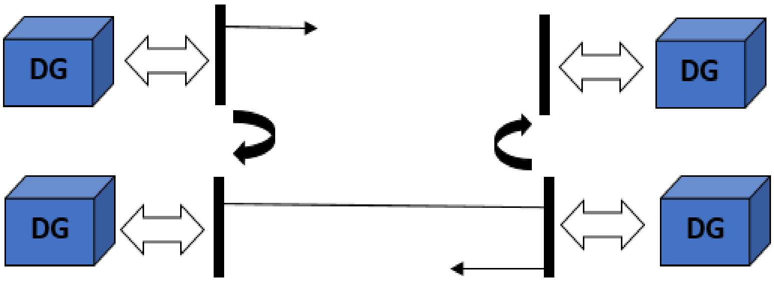
This case study gives a deeper insight into the importance of having controllable storage devices which are able to compensate for fluctuations in frequency in order to assist the microgrid system in restoring stable steady state operation.

In addition to controllable storage devices in an islanded microgrid system, having a secondary frequency-load control strategy means working in conjunction with a controllable storage devices mean that the microgrid system is able to implement selective load shedding strategies. This ultimately increases the reliability of the microgrid system as it will have the capability not only to restore itself to a stable operation after experiencing disturbances, but it is able to intelligently discern the safest method in which to do it.

6.3 PowerWorld Simulation

Aims:

The final component of this thesis investigation is comprised of a performance study of a given microgrid when it used the droop control technique to regulate the system voltages as well as the load sharing capabilities of the different sources. As was mentioned previously – droop control decouples power, voltage and frequency and allows us to form output characteristics for the microgrid, which can be controlled by traditional grid control methods [12]. A schematic diagram of the system that is to be studied is presented below in figure 6.3-1, which was adopted by a study performed by Glover [51].



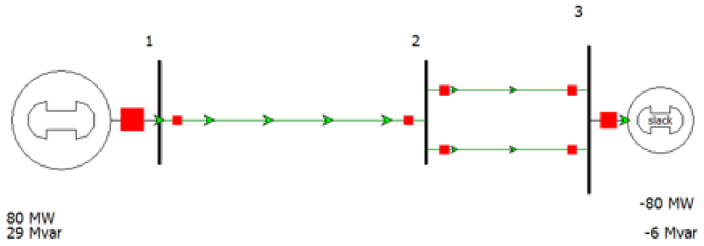
6.3- 1:Glover Microgrid Schematic[51]

Method & Background:

For the sake of modelling and analysing this microgrid design, this thesis project utilised PowerWorld's simulation software. PowerWorld has the capability to carry out transient stability analysis as well as implement droop control networks [18]. The following section of this thesis will provide an overview of how the given microgrid network was implemented using the PowerWorld software.

1. Power Flow

As was established in chapter four - in order to design an effective control strategy, a method of determining the key variables of a microgrid system is required [29]. The power flow is used to determine the steady-state operating condition of the power system and is implemented in PowerWorld by initiating the simulation in run mode - where the green arrows indicate the flow of power in the system as shown below in 6.3-2.



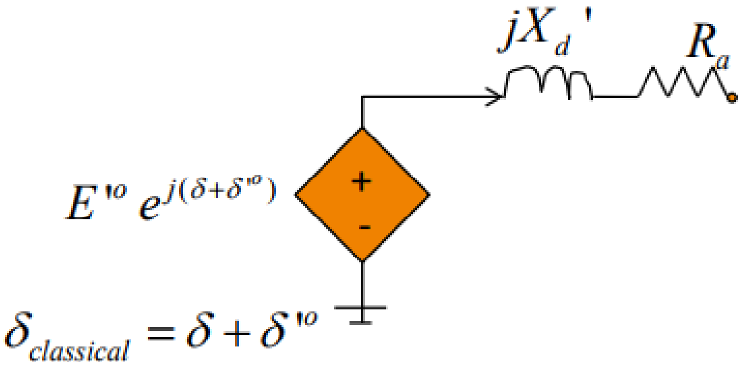
6.3- 2:Power Flow Analysis in PowerWorld

2. Transient Stability

The transient stability of a synchronous power system is defined as its ability to return to stable operation and maintain synchronism despite experiencing a significant disturbance [18]. This disturbance might be the occurrence or clearing of a fault, or the switching of a circuit element for example. The transient ability of a system is a good indicator of its stability – therefore, it will be implemented in this thesis as a test of the islanded microgrid which was presented in the previous section and can be set up in the transient stability analysis tab in PowerWorld, as shown in Appendix A.

3. Generator Modelling

PowerWorld also possesses the ability to model various types of generators which each have several classes of models assigned to them such as exciters and stabilizers for example [18]. However, for the sake of simplicity – the classical model, GENCLS is preferred for analysis in PowerWorld. It represents the machine dynamics well by defining a fixed voltage magnitude behind a transient impedance as shown below in figure 6.3-3.



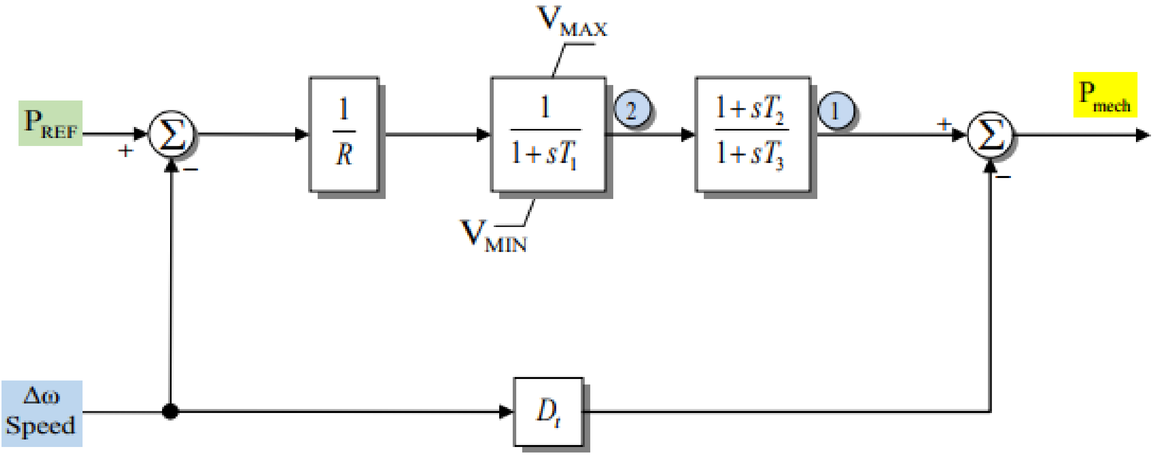
6.3- 3: PowerWorld GENCLS Generator model

4. Prime Movers & Governor Models

The rotational steady-state speed of a given synchronous machine is determined by the speed of its prime mover. The prime mover is essentially a machine or component which can covert an initial form of energy into mechanical energy [18]. Typical examples are diesel engines, gasoline engines, steam turbines and hydro-turbines.

Governors, however, are designed to be able to sense the speed of the prime mover and control the speed in order to maintain it at a desired level by comparing it to a reference speed. Therefore, the governor's function is that of a controller which is able to regulate the speed and frequency of a prime mover so that it can be used for specific tasks.

Governor models can be implemented into PowerWorld by inputting the requisite parameters in order to implement the feedback loop displayed in the schematic diagram in figure 6.3-4 below.



6.3- 4: PowerWorld System Governor Machine Model [49]

5. Droop Control and Droop coefficients

Droop may be defined as the decrease in speed of a synchronous generator as its load increases. Without a form of droop control, this load increase will eventually cause the machine to slow down to a halt. A governor however has the ability to increase the fuel going into the synchronous machine – which in turn would increase the speed to a desired level [18].

PowerWorld is able to emulate the function of droop control by appropriately tuning and implementing the governor machine models which have been covered above. This tuning consists of inputting the corresponding droop coefficients into the governor models. Droop coefficients, otherwise known as speed-droop coeffients, can be described as factors which influence the speed control of generators [52].

In this thesis project, the droop coefficients of each of these generators were determined by way of simulation through the use of transient stability analysis techniques found in the Power World software. They have the purpose of maintaining promoting load sharing amongst the network's generators, maintaining stable operation, stable operation as well as reducing changes in generator frequencies after changes in load.

The mathematical origin and definition of the droop co-efficient for inductive lines is derived from the droop controller equation for a given frequency displayed below;

$$P = \frac{1}{m}(\omega - \omega o)$$

Where P is a measure of active power

When this equation is written as an offset from a given set point of P_{ref} and the frequency is normalised through the division of the nominal frequency, the following equation can be derived;

$$P = Pref - \frac{1}{\rho}\left(\frac{\omega - \omega o}{\omega o}\right)$$

Where ρ is the droop co-efficient

Through solving for the droop co-efficient, ρ, a relationship can be formed whereby the coefficients for each of the generators can be found and the final derivation is given below;

$$\rho \ = \frac{1}{\Delta P} \times \frac{\Delta f}{f}$$

Finally, as mentioned previously, droop coefficients have the purpose of maintaining promoting load sharing amongst the network's generators, maintaining stable operation, stable operation as well as reducing changes in generator frequencies after changes in load. The following equations prove this functionality;

Proportional changes mechanical power between the generators for changes in load power is represented by;

$$\rho_1 = \rho_3 = \rho_6 = \rho_8$$

Proportional changes in supply power between the generators for changes in load power is therefore represented by;

$$\therefore \Delta P_1 = \Delta P_3 = \Delta P_6 = \Delta P_8$$

Changes in frequency minimised and stable operation is maintained according to;

$$\frac{\Delta f}{f} = \Delta \mathrm{P} \times \rho$$

6. Load Models

Load definitions in PowerWorld fall into one of two categories – static load models and dynamic load models. This thesis however, will define all loads as static load models. These type of loads are normally a function of voltage and/or frequency and are defined as follows:

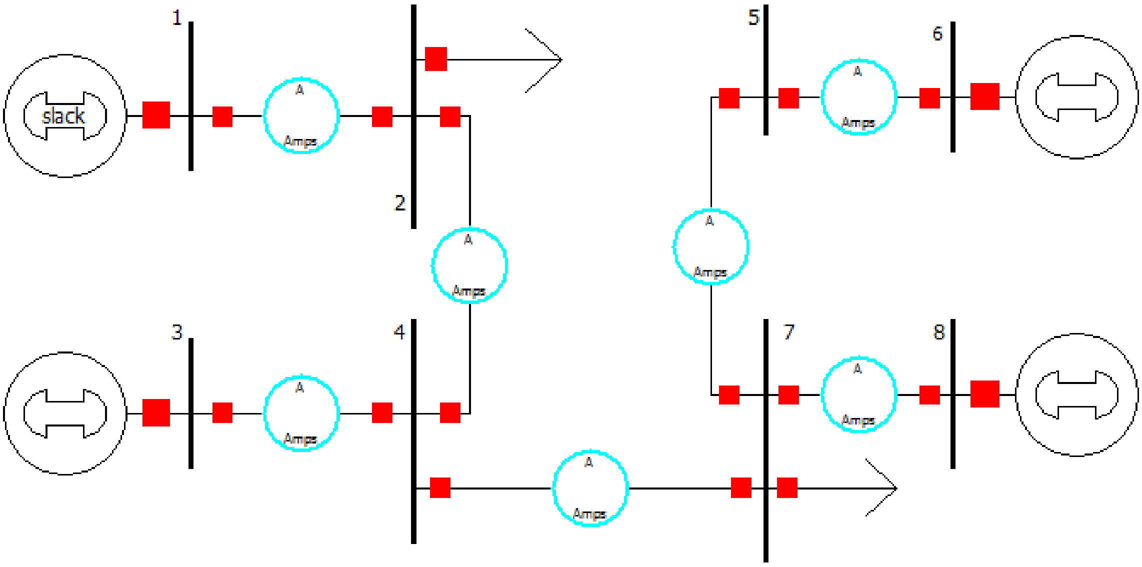
$$P = P_{LOAD} \times (1 + a_7\Delta f)$$

$$Q = Q_{LOAD} \times (1 + a_7\Delta f)$$

Where P_{LOAD} and Q_{LOAD} are the nominal output active and reactive powers respectively and a_7 is the frequency dependent variable found in the "stability" tab in the load dialogue window in PowerWorld. An example of this process is shown is Appendix A.

Simulation:

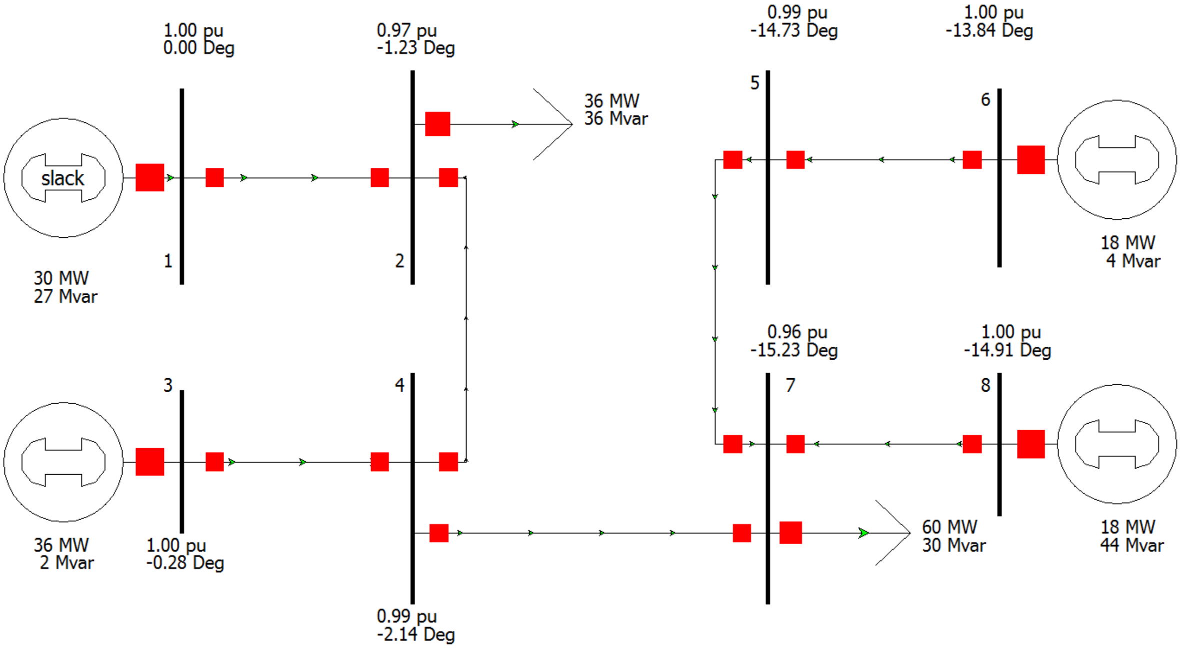
Now that a description of how droop control may be implemented in PowerWorld has been presented, this thesis can now proceed to present the simulation which was carried out to investigate P-f droop control. The schematic of the model microgrid discussed in the previous section is presented below in figure 6.3-5.



6.3- 5: PowerWorld Simulation of Schematic Model

With the models set in place and the appropriate specifications applied, a simulation of the droop control system was conducted. The simulation was able to provide numerous metrics of the systems stability including the generator frequencies, speeds and active powers. Starting with the load flow analysis, we can see from figure 6.3-6 below that the microgrid system is operating in a stable manner as most of the bus voltages are close to 1.00 p. u, which means that all areas of the microgrid is receiving a requisite amount of power.

1. Power Flow Analysis

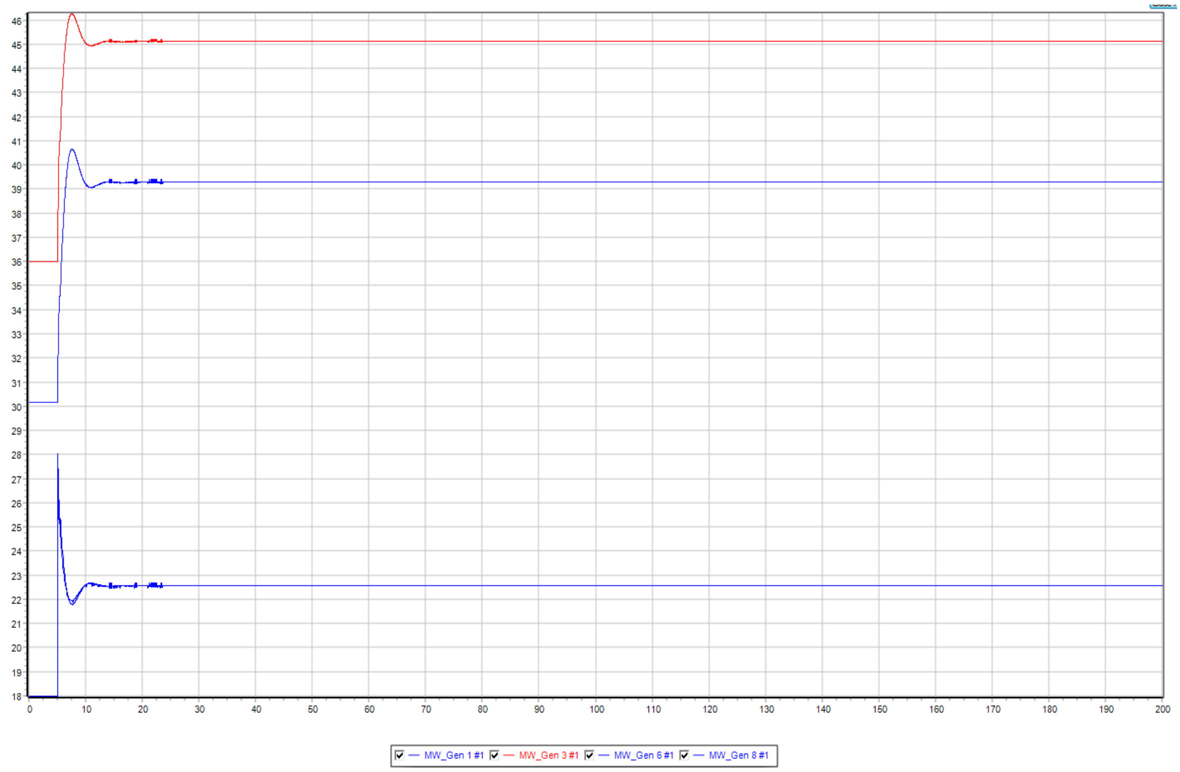


6.3- 6: PowerWorld Power Flow Analysis

2. Transient Stability Analysis – Step Changes in Load

As previously stated, the transient stability of a synchronous power system is defined as its ability to return to stable operation and maintain synchronism despite experiencing some significant disturbances [18]. In order to implement this situation in power world, it was necessary to introduce step changes in load in order to analyse how the microgrid system responded. The next section of thesis will highlight the system's transient response after load changes.

Figure 6.3-7 below displays the system's transient response to sudden increase in load by 33.3% on a scale of power vs. time. The graph clearly demonstrates that the initial state of each generator matches the power ratings specified in the original design, with the graphs reading 36 and 30 MW for generators 1 and 2 respectively, and 18 MW for generators 3 and 4.

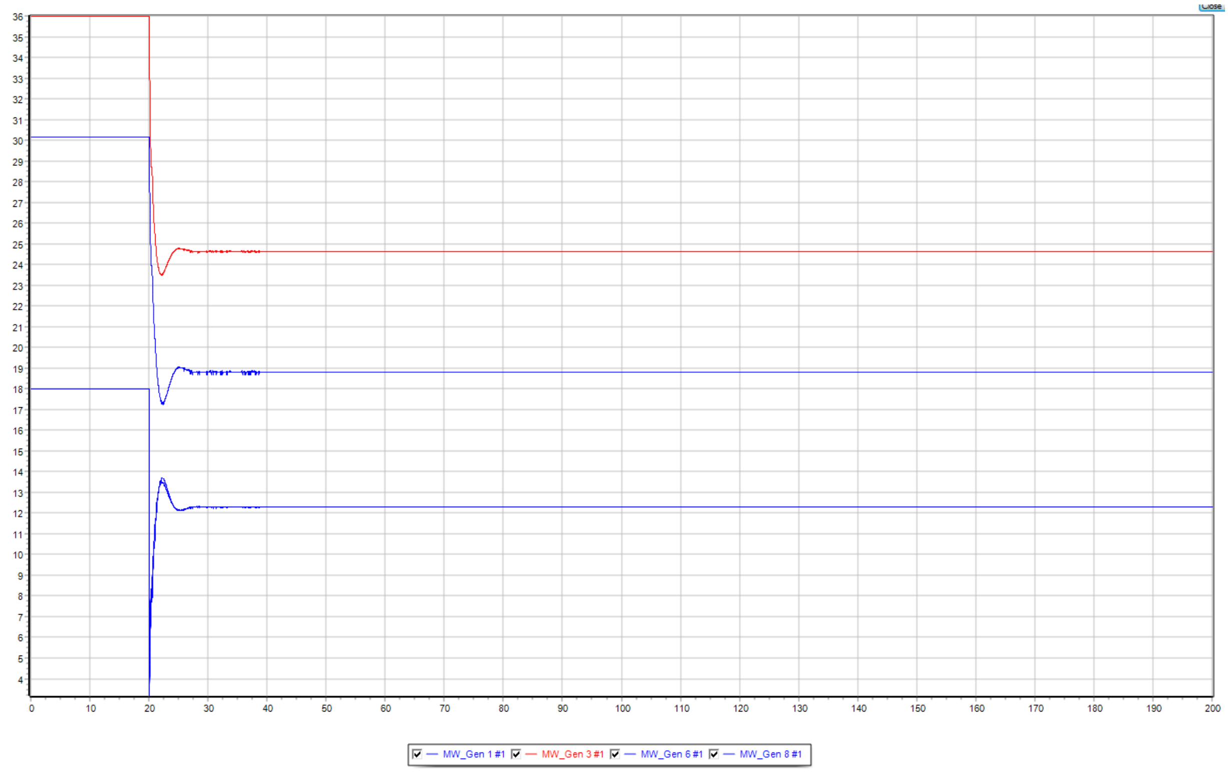


6.3- 7: Transient Response to 33.3% Load Increase

The point of interest however, occurs when time equals 5 seconds – when the step increase in load was initiated. Each of the graphs show a similar response, there was an initial overshoot in power that indicates the generators reacted accordingly to the increase in load. However, once the power had overshoot the requisite power level, the power levels of the generators then dropped below the requisite power level before eventually settling on the desired power level.

This response is a positive indication that the governor models associated with each generator are functioning correctly and are allowing the system to exhibit droop control in order to ensure the system continues to function in a stable manner in spite of disturbances which might occur. Therefore, in this instance – droop control is operating in an optimal manner.

The reverse test was carried out on the islanded microgrid system and this time a total load decrease of 33.3% was induced into the system. Figure 6.3-8 below displays the system's transient response to this load decrease on a scale of power vs. time. Once again the graph demonstrates that not only were the initial states of each generator initially preserved, but the droop control enforced by the governor models associated with each generator were able to overcome the disturbance induced into the system.

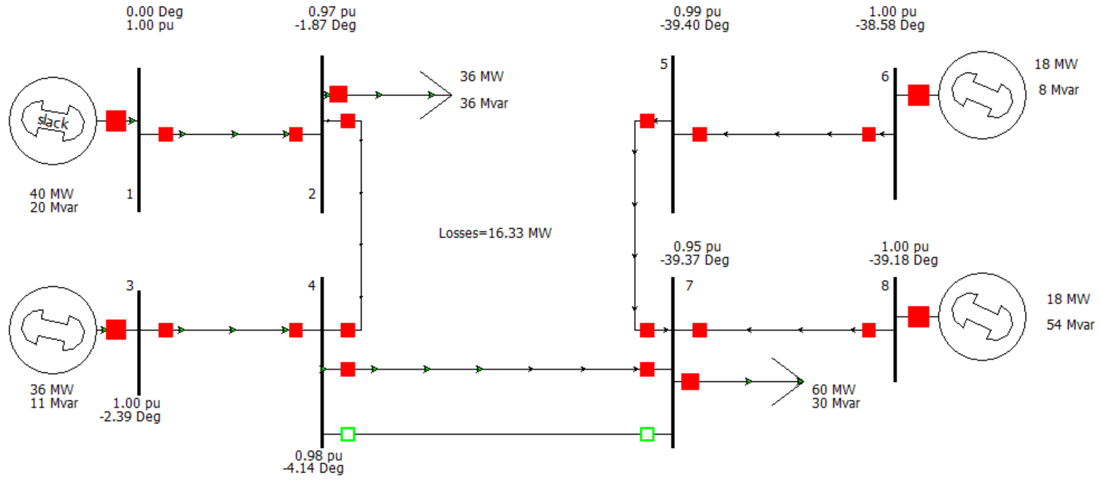


6.3- 8: Transient Response to 33.3% Load decrease

2.1 Transient Stability Analysis – Emergency Situation

At this point of the thesis investigation, the given islanded microgrid simulation has been tested under the conditions of unexpected changes in load which were intended to mimic disturbances the system may encounter. The next stage of the transient stability analysis will be to subject the islanded microgrid system to an emergency situation - whereby one of the lines in the system is taken out of service in order to mimic a fault situation.

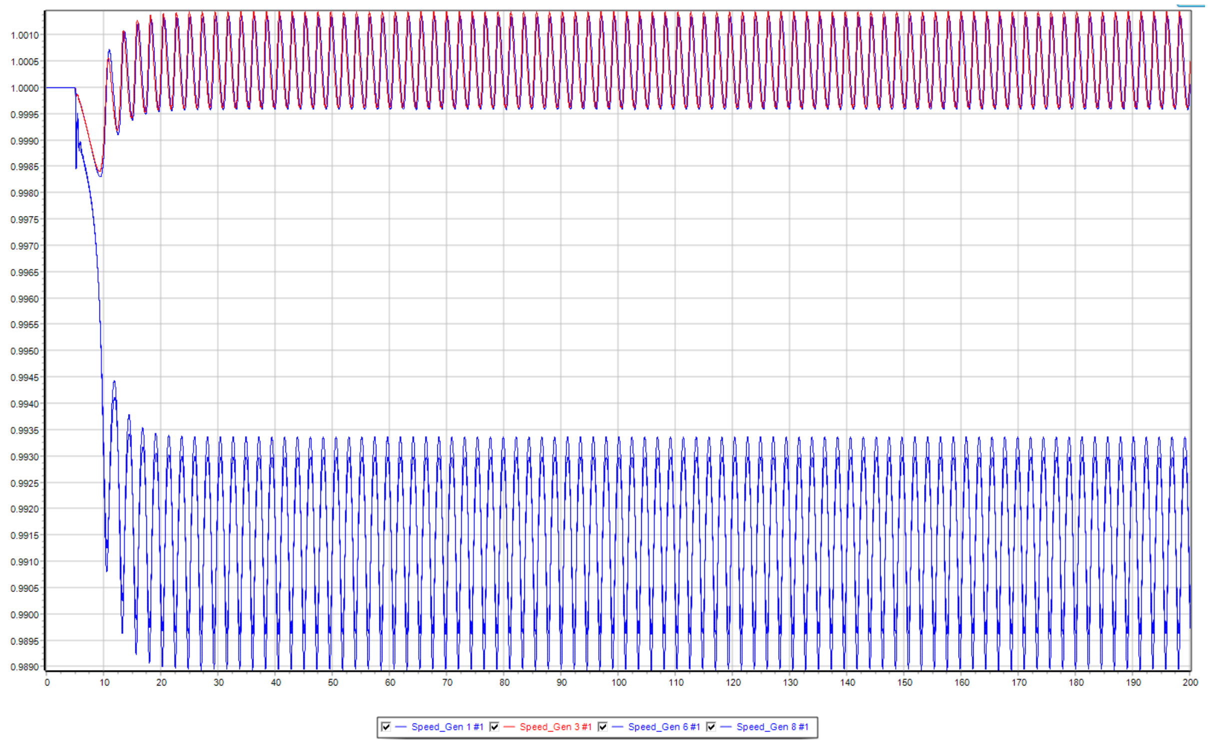
In the case of this thesis, this fault situation was created by disconnecting the line in the system. By doing this, the system is now operating in a manner which it was not designed to, therefore a transient stability analysis in this instance will provide a good level on insight as to how the system performs in emergency situations. Figure 6.3-9 below displays the power flow analysis of the given microgrid system operating in an emergency situation.



6.3- 9: PowerWorld Performance in Emergency Situation

Once the emergency fault situation had been defined in the given islanded microgrid system, another transient stability analysis process could then be conducted on the system. With this in mind, a step changes were introduced into the system at the same intervals which were studied in earlier sections.

Figure 6.3-10 below displays the islanded microgrid's system's transient response in the fault situation after a 33.3% load increase.



6.3- 10: Microgrid generator speed response in the fault situation after 33.3% load increase.

As can be observed from the graph displayed above, in the case of an emergency situation – the generator speed responses displayed oscillatory behaviour. While this behaviour suggests that the governor models have failed to enforce droop control upon the generators – it is in fact the governors that are causing the oscillatory behaviour. This is because in the first instance the governors were able to readjust the outputs of the generators after they had initially overshot the desired power outputs.

In this case however, the governor is causing the generators to oscillate because it is readjusting the overshoots in both directions, but never reaching a steady state as was observed in previous sections. Therefore the speed of the generators becomes oscillatory in its nature which implies that this islanded microgrid system isn't stable in this instance, which is undesirable. Therefore, the next section of this thesis is dedicated to the analysis of this situation and devising methods to limit, or improve this situation.

Investigation & Findings:

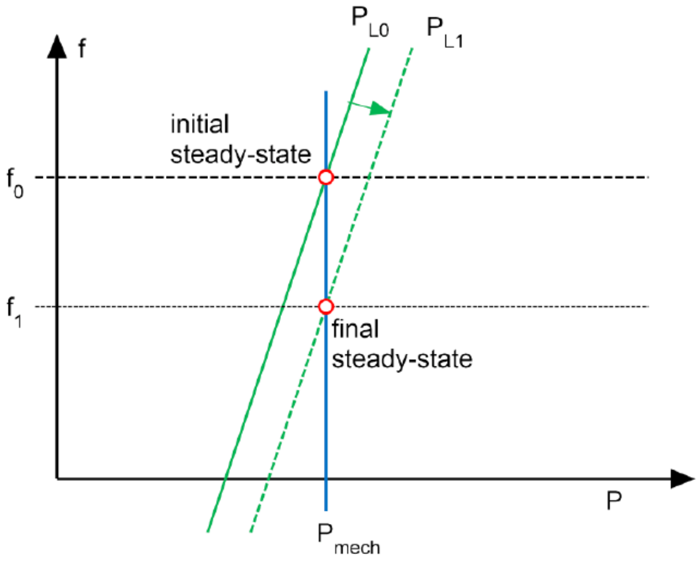
It was discovered during this simulation that the governor models associated with the generators of the islanded microgrid were able to successfully implement P-f droop control functionality for the system in the event of disturbances associated with changes in load. However, in the emergency situation of a fault occurring on one of the lines – the droop control strategy failed to keep the microgrid system stable.

This investigation will aim to Identify areas where the P-f droop control method can be improved upon in order for it to be able to mitigate or reduce the impact the fault has on the operation of droop control on the islanded microgrid. By conducting this investigative process, it is hoped that ideas for creating innovative control strategy for the control of an islanded microgrid will be developed as was stated in the introductory sections of this thesis project.

Droop Co-efficient adjustments:

At this stage of the droop control investigation, the main focus has been the response of the P-f droop control system with respect to power. However, changes in the network's frequency can also have detrimental effects on the functionality of a droop control system. This is because droop control is the primary stage of control of a microgrid, and its implementation may result in steady state deviations in frequency which can only be reduced or removed by secondary level control [52].

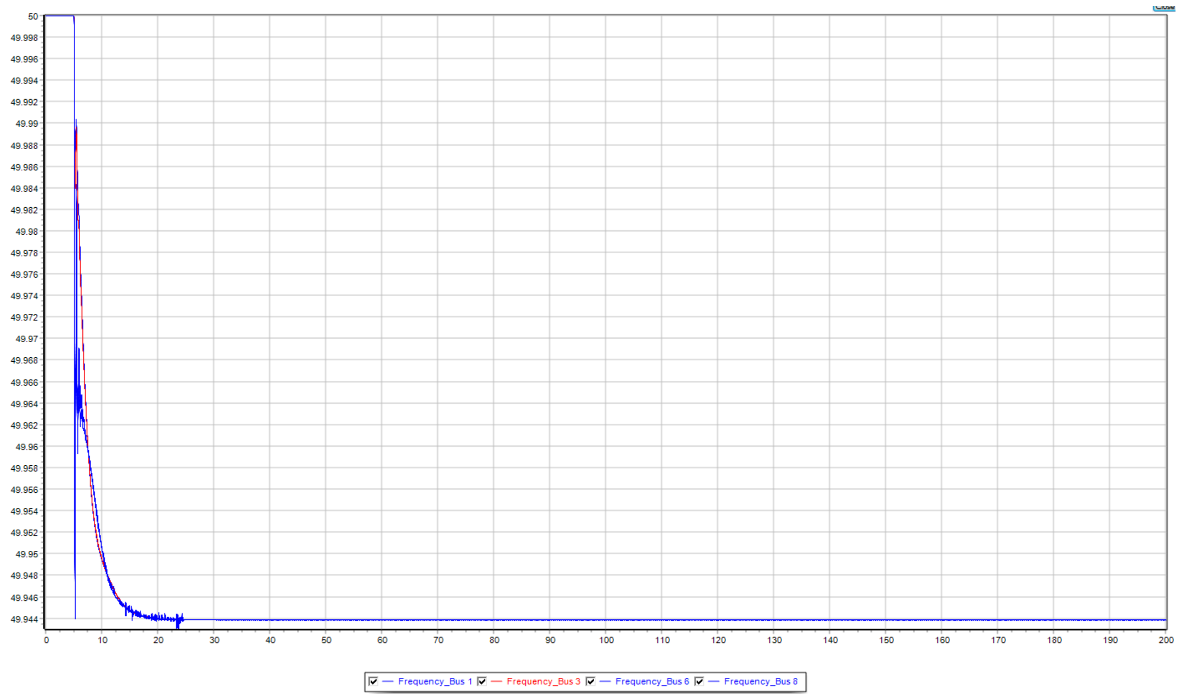
Figure 6.3-11 below provides a visual representation of how the power and frequency of a droop controlled system are affected after a change in load. The graph shows that when there is an increase in load in the system, more power is delivered by the generators in order to compensate for the shortfall in supply.



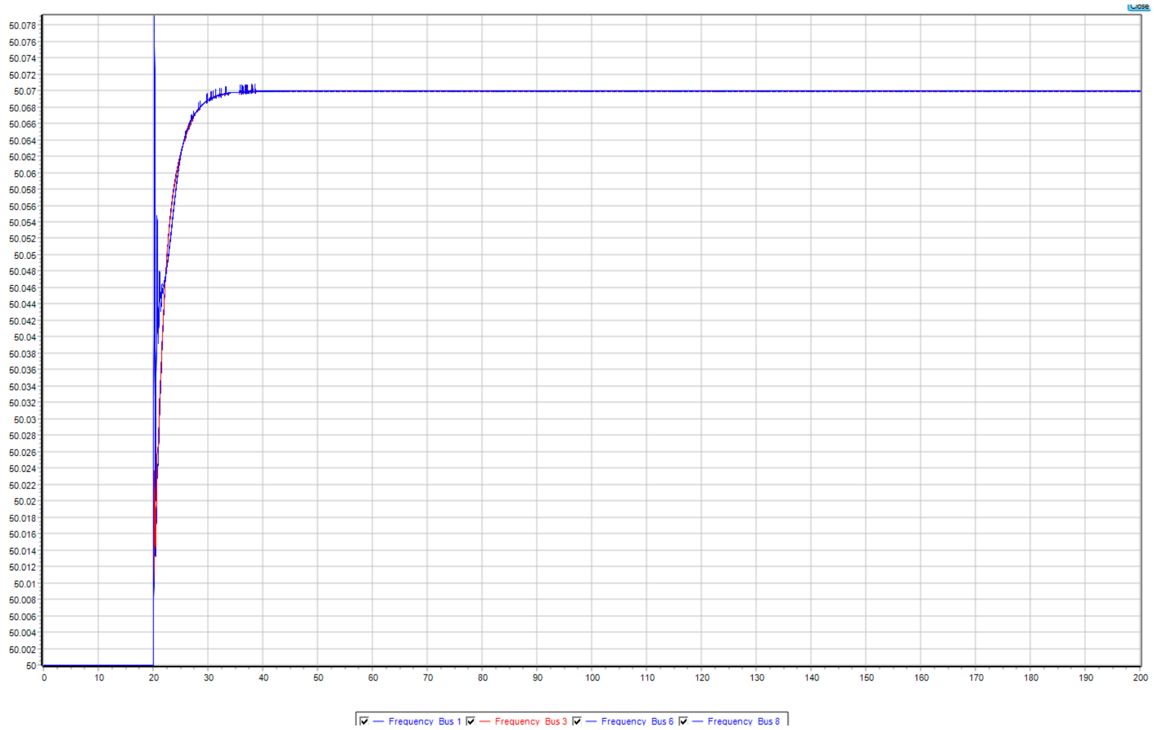
6.3- 11: P-f Chart after change in load [51, 52]

However, this produces a decrease in generator frequency which is characterised by the drop in frequency from f_0 to f_1, meaning that the generators slow down. Therefore a new steady state operating point is reached. This is not always a desirable outcome, and therefore a secondary control strategy can be implemented to improve on this effect.

This secondary control method can be implemented by utilising the droop coefficients associated with the governor models which dictate the P-f droop control operation. Figure 6.3-12 below shows the effect the increase in load had on the microgrid system, where the frequency response of the generators experienced a minor dip in frequency from 50.1 Hz to 49.9 Hz. While this is a minor drop, the adjustment of droop coefficients in the governors could be applied in order to remove this discrepancy. Figure 6.3-13 shows the effect the adjustment of droop coefficients has as the frequency was returned to a more ideal value of 50.07 Hz.

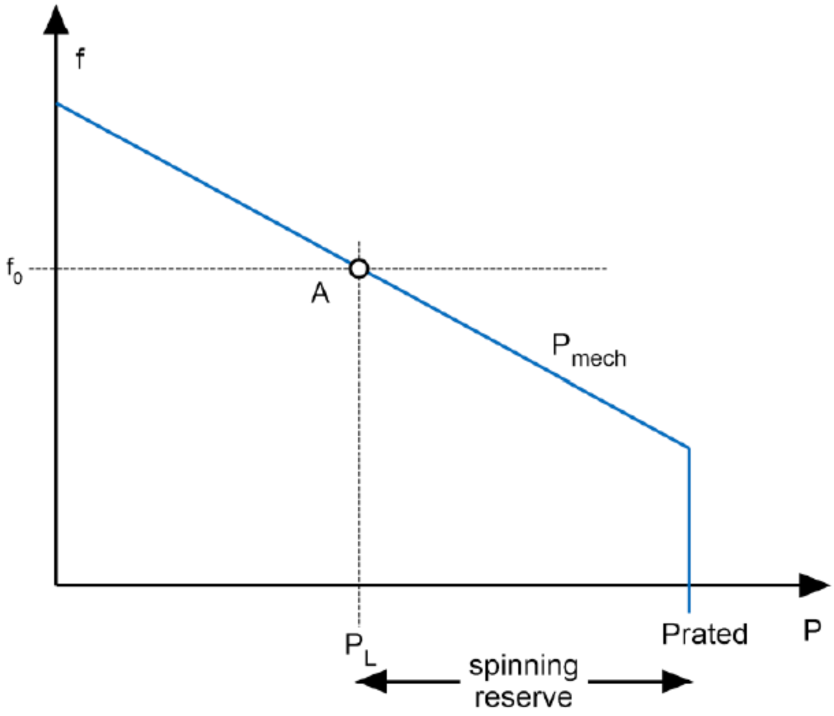


6.3- 12: System response before droop coefficients adjustment



6.3- 13: System response after droop coefficients adjustment

While adjusting the droop coefficient values is a good method for controlling the frequency deviations caused by the application of droop control to the microgrid system, there is a limit associated with the amount of power the generator can supply into the system [51, 52]. This concept is visually presented below in figure 6.3-14 and highlights that the maximum power the generator can supply is based on its rating. The difference between the operating point of the generator and its maximum rating is called the "spinning reserve".

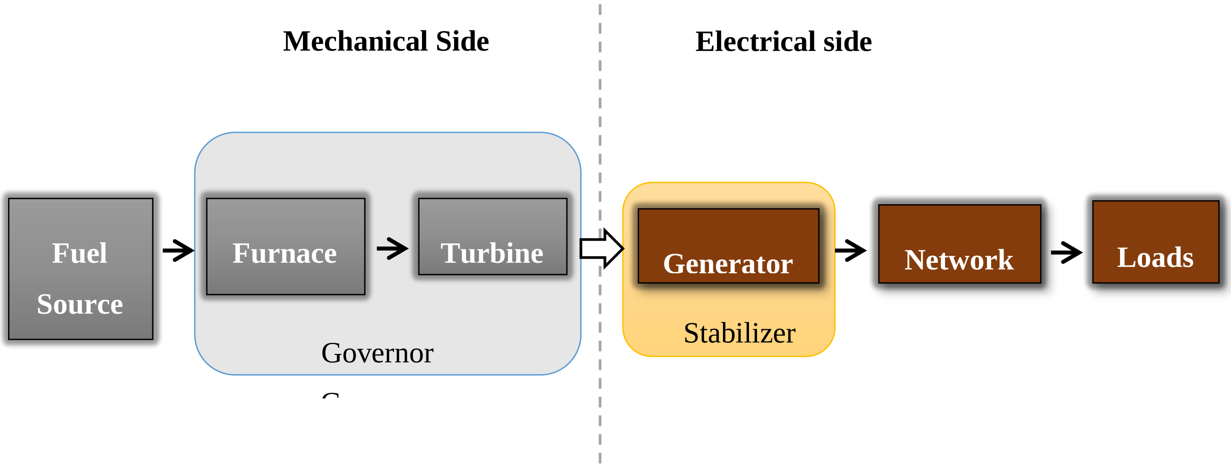


6.3- 14: Generator Spinning Reserve

Therefore, it is important to find a balance with the value of the droop coefficient so that the generators can reach a stable operating point which won't descend into instability when met with disturbances. Another important consideration to be made is that the chosen droop coefficient must ensure that changes in mechanical power correspond to small changes in frequency while also maximising output power.

Stabilizer Control:

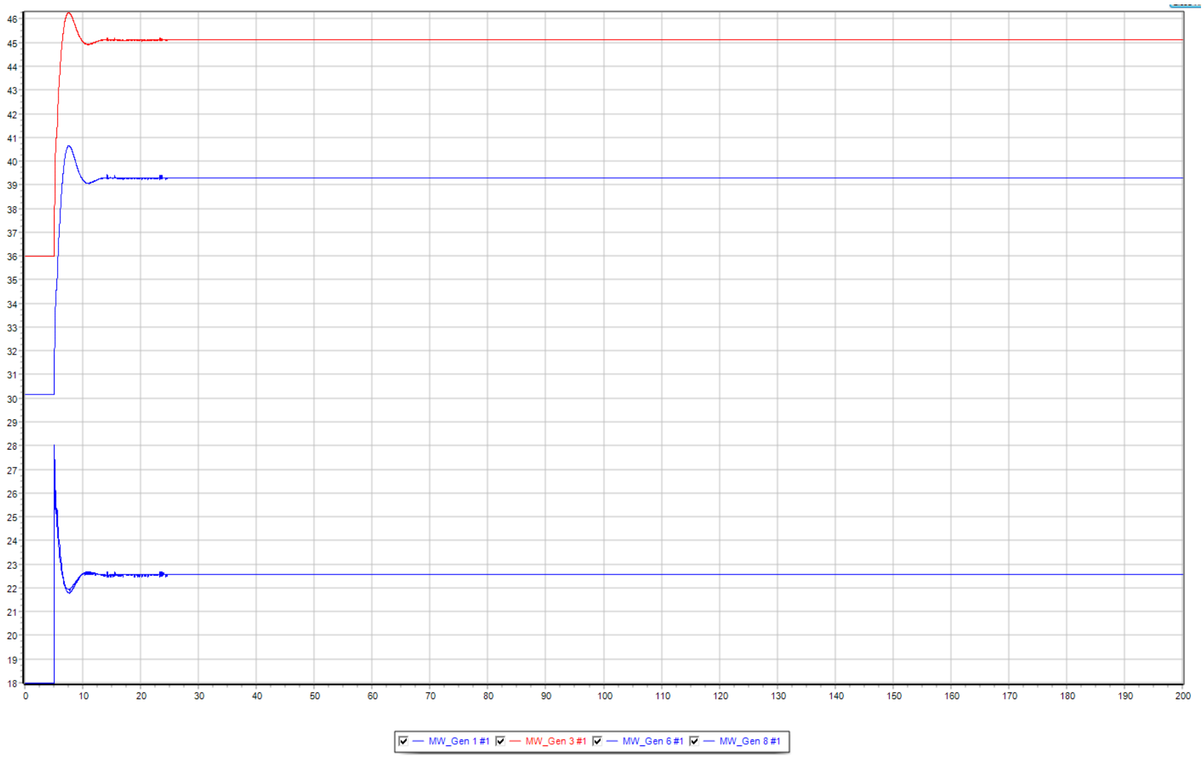
Another key consideration that can be made in order to improve the functionality of the P-f droop control method which was presented in chapter 6, is to adjust the transient stability models of the generators which have been used in PowerWorld. While a governor in itself is enough to implement P-f droop control into the microgrid system, adding other elements to the transient stability models of the generators can improve the overall performance of the simulation. Figure 6.3-15 below presents the physical structure of a given power system.



6.3- 15: PowerWorld Machine Model Schematic

As can be seen from figure 6.3-15 above, a power system is a combination of various elements and systems which work in unison to transfer energy from a mechanical form into an electrical form in order to supply energy to specified loads. On the mechanical side of things, we can see that the governor is responsible for the control of pressure or speed which the fuel source – be it diesel, gas or steam - is fed into the boilers, furnaces or turbines [18]. This is why the governor is crucial to the stability of the system as far as

The stabilizer is a device which is designed to reduce variations in the supply of the generators into the rest of the system [18]. Stabilisers derive their signals from the machine speeds, frequencies or powers of the generator and are typically activated when low frequency oscillations are detected in the operation of the generators [18]. Therefore, the implementation of a stabilizer to the transient stability model can assist in offering stability to the system’s operation in droop control when a fault occurs. The implementation of a default IEEE stabilizer, which is able to stabilise the operation of the droop control system while it’s under fault conditions as is shown in Appendix A.



6.3- 16: System Response after Stabilizer Application

At this stage of the thesis, two of the three initial project objectives have been met. However, due to various difficulties including the broad nature of the topic, the availability of topic specific resources and the technical limitations associated with modelling softwares, this objective could not be achieved.

In light of this, the focus of this thesis instead became a research focused development of a convenient body of work which may serve as a point of reference for future works in this area of study.

Chapter Seven– Project Conclusion

7.0 Project Outcomes

Due to the fact that the aim of this project was changed into becoming a research focused project, the focus was concerned with the development of a convenient body of work which may serve as a point of reference for future works in this area of study. This thesis provides a basis of background and technical knowledge that may give the reader a broad and detailed understanding of the microgrid and the associated control strategies in a convenient manner.

When these factors are considered, the usefulness of this project becomes clearer. By going through this investigative process, a list which highlights some important factors and issues concerned with the control of an islanded microgrid has been developed. This work may provide a basis for future studies in this area of expertise, and also reduce the need for background research as a large majority of it is covered in this project. This means that this study can help in reducing the time associated with the extra information gathering. This can improve the efficiency of those who may want to continue work in this area of study. These findings of this thesis study are summarised below:

1. P & PI Controller Regulation & Response Times
2. Natural Load Sharing Amongst Distributed Generators in Microgrids
3. Secondary Frequency-Load Control Mechanisms in Microgrids
4. Controllable Storage Systems Implemented in Microgrids
5. Automated Load Shedding in Microgrids
6. Stabilizer Control Strategies in Microgrids

7.1 Recommendations and Future Work

This thesis has explored multiple existing strategies for the control of islanded microgrids and then conducting an investigation to identify the areas where the existing methods can be altered in order to reduce or mitigate common operational issues. The final goal was to use the gathered information to finally develop an innovative strategy that may be used to control the microgrid – however, due to various limitations discussed in section 6.3 this wasn’t achieved.

This meant that the aim of this thesis was changed into becoming a research focused development of a convenient body of work which may serve as a point of reference for future works in this area of study.

Whilst this study provided a technical and theoretical background on the study of an islanded microgrid, future work could focus on the analysis of the microgrid’s demand response, the effect of a battery and renewables in a microgrid system and their effects on stability.

Additionally, future work could focus more on the theory behind secondary and tertiary control methods as this thesis primarily focused on primary control methods. Another consideration that can be made is the study of power flow techniques used within the simulation software that will be used to implement the control techniques of the islanded microgrid.

7.2 Conclusion

This thesis has provided and highlighted an investigative process into the study of the control of an islanded microgrid. This was demonstrated through the research and exploration of multiple existing control techniques for the control of a microgrid and then conducting an investigation to identify the areas where the existing methods can be altered in order to reduce or mitigate common operational issues. The final goal was to use the gathered information to develop an innovative strategy that may be used to control the microgrid. However, due to various challenges faced over the course of the project this goal wasn't achieved.

In light of this however, the focus of this thesis instead became a research focused development of a body of work which may serve as a point of reference for future works in this area of study.

This means that this thesis may prove to be a useful resource in studies which focus on the creation of an innovative control strategy for an islanded microgrid. Some of the key factors and considerations that were found to be impactful in the control of an islanded microgrid over the course of this research project are listed below;

1. P & PI Controller Regulation & Response Times
2. Natural Load Sharing Amongst Distributed Generators in Microgrids
3. Secondary Frequency-Load Control Mechanisms in Microgrids
4. Controllable Storage Systems Implemented in Microgrids
5. Automated Load Shedding in Microgrids
6. Stabilizer Control Strategies in Microgrids

By going through this investigative process, it is possible that the list of factors and considerations found in this thesis project may be a useful resource for future studies performed in the topic of islanded microgrid control.

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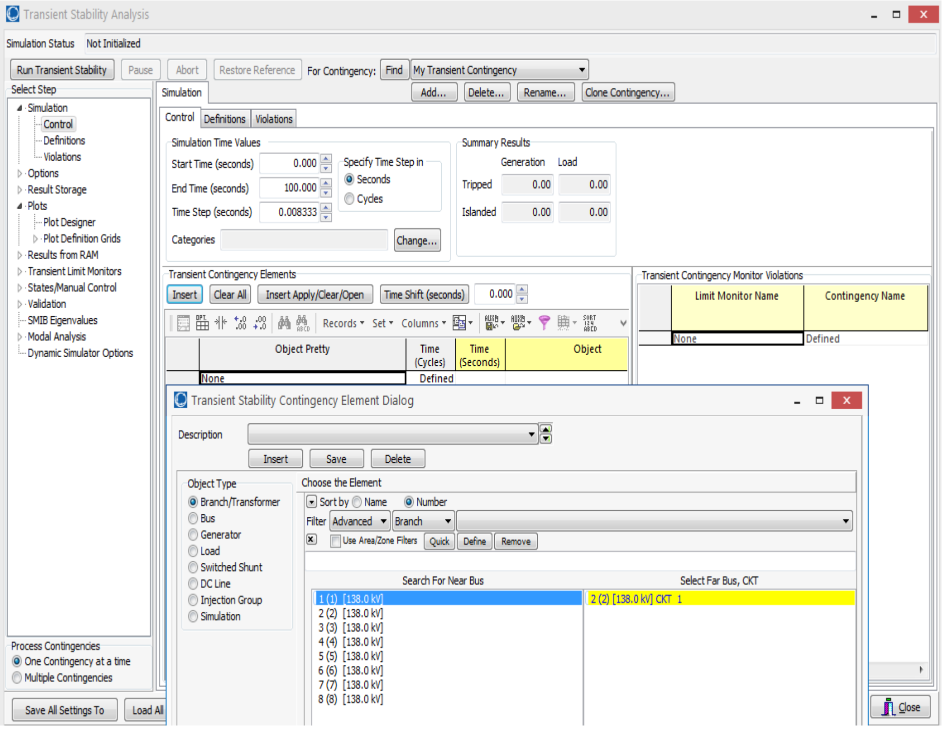
9.0 Appendices

Appendix A: PowerWorld Inputs



Simulation Status: Not Initialized

For Contingency: My Transient Contingency

Simulation Time Values
Start Time (seconds): 0.000
End Time (seconds): 100.000
Time Step (seconds): 0.008333

Specify Time Step in: ● Seconds ○ Cycles

Categories:

Summary Results

	Generation	Load
Tripped	0.00	0.00
Islanded	0.00	0.00

Transient Contingency Elements: Time Shift (seconds) 0.000

Object Pretty	Time (Cycles)	Time (Seconds)	Object
None	Defined		

Transient Contingency Monitor Violations

Limit Monitor Name	Contingency Name
None	Defined

Process Contingencies
● One Contingency at a time
○ Multiple Contingencies

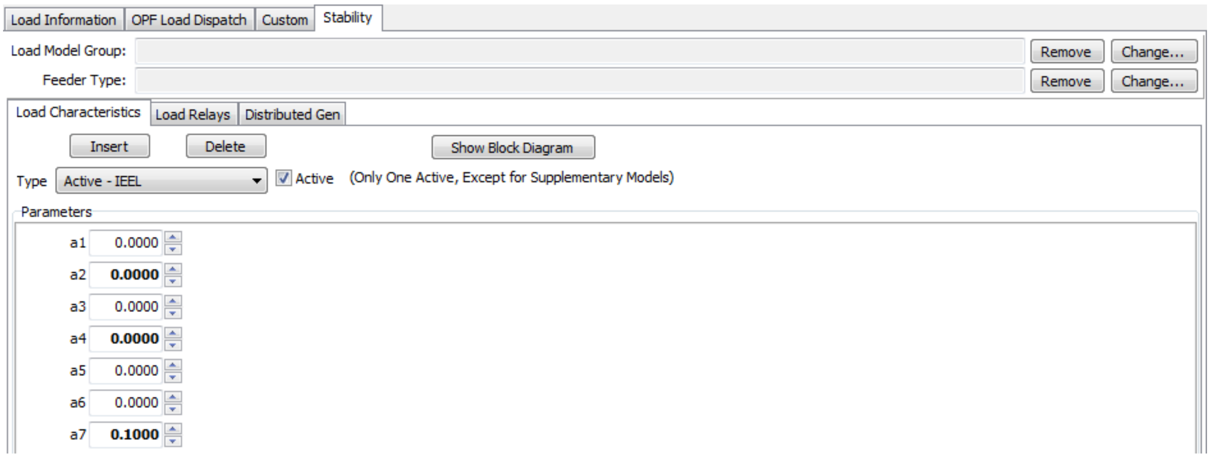
Description:

Object Type
● Branch/Transformer
○ Bus
○ Generator
○ Load
○ Switched Shunt
○ DC Line
○ Injection Group
○ Simulation

Choose the Element
☑ Sort by ○ Name ● Number
Filter: Advanced; Branch
☒ ☐ Use Area/Zone Filters

Search For Near Bus	Select Far Bus, CKT
1 (1) [138.0 kV]	2 (2) [138.0 kV] CKT 1
2 (2) [138.0 kV]	
3 (3) [138.0 kV]	
4 (4) [138.0 kV]	
5 (5) [138.0 kV]	
6 (6) [138.0 kV]	
7 (7) [138.0 kV]	
8 (8) [138.0 kV]	

PowerWorld Transient Stability Analysis Set-Up



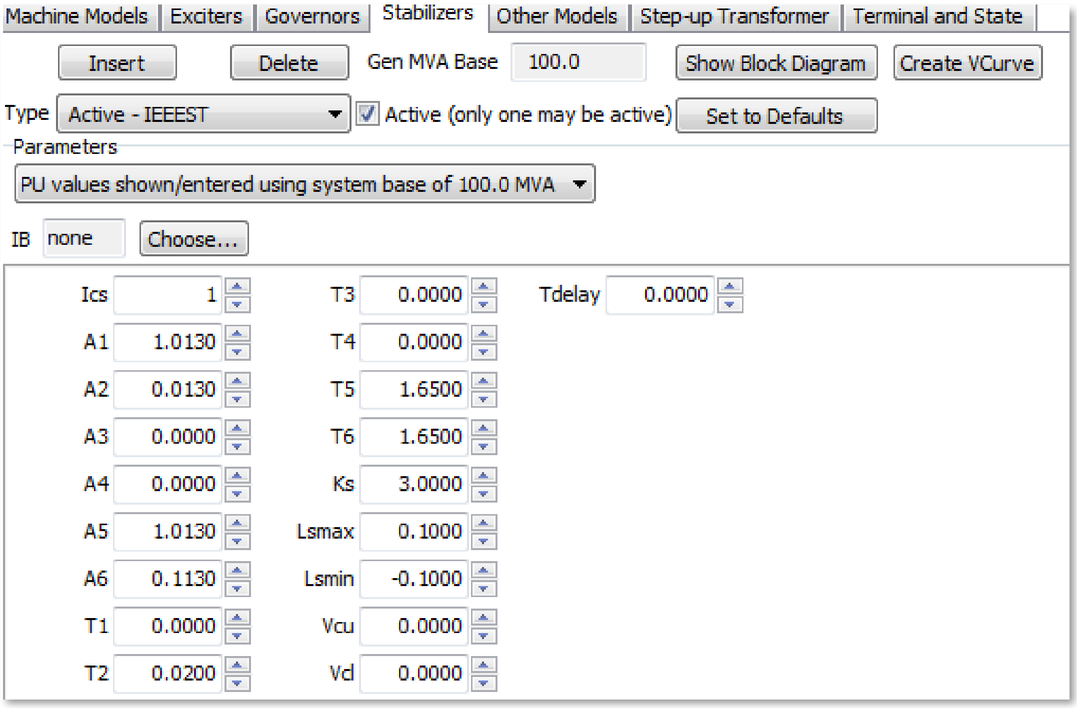
Load Model Group:

Feeder Type:

Type: Active - IEEL ☑ Active (Only One Active, Except for Supplementary Models)

Parameters
a1 0.0000
a2 0.0000
a3 0.0000
a4 0.0000
a5 0.0000
a6 0.0000
a7 0.1000

Frequency Dependent Loads in PowerWorld



Gen MVA Base 100.0

Type Active - IEEEST

☑ Active (only one may be active)

PU values shown/entered using system base of 100.0 MVA

IB none

Ics	1	T3	0.0000	Tdelay	0.0000
A1	1.0130	T4	0.0000		
A2	0.0130	T5	1.6500		
A3	0.0000	T6	1.6500		
A4	0.0000	Ks	3.0000		
A5	1.0130	Lsmax	0.1000		
A6	0.1130	Lsmin	-0.1000		
T1	0.0000	Vcu	0.0000		
T2	0.0200	Vcl	0.0000		

PowerWorld Stabilizer implementation (IEEE Default)