EMBEDDED MICRO GRID DESIGN & APPLICATION FOR IMPROVEMENT IN MAIN GRID PERFORMANCE AND SUSTAINABILITY

Hayley O'Sullivan

Murdoch University

Final Year Thesis Submission

Department of Engineering & Computing

South Street Campus, Perth WA

April 2016

I dedicate this Thesis to the Almighty God, who provides me with everything I need. And His son, Jesus Christ, who always gives me the strength to face whatever challenges that come my way.

SUMMARY / ABSTRACT

This Thesis focusses on the practical application of Micro grid design in Western Australian, discussing current conditions of the main grid, challenges of micro grids, and how micro grid control can be used to improve the performance of the main grid.

Using the case study of the Kalbarri LV grid, I created and implemented the design according to area needs and specifications on PowerFactory, taking into account assumptions made with the static load.

I then compared different types of Master- Slave control strategies to compare which had the most positive effect on the grid in reliability and efficiency.

Different from proposed strategies, Voltage controlled master and current controlled slaves ended up being the most appropriate choice for grid connected mode due to increased reliability, efficiency and practical design in regards to transition from grid connected mode to Isolated mode and vice versa. The main reason for this is that the main grid control strategies were not enough to maintain recommended voltage limits to this feeder in an end of line scenario, due to the long distance.

Standardization for micro grids in regards to control requires individual assessment in regards to the micro grid’s purpose, whether it be to go unnoticed in a grid or increasing the performance of the main grid.

ACKNOWLEDGEMENTS

I would like to thank first and foremost my supervisor, GM Shafiullah, for all his amazing mentoring and guidance over the course of this Thesis. I would also like to thank my contacts at Western Power; Dean Frost, Phil Capper, Sakshi Priya, Vic Roque and Colin Black for all their help in getting the data and direction that I needed. And to my friends and family, who kept me sane during this time.

CONTENTS

List of Figures

1 INTRODUCTION

1.1 Aim of the Project

This Thesis has several main objectives. The first is to assess whether there is a need for Micro-grids, focussing mainly on the Western Australian electricity grid. Secondly, to evaluate an area in the Western Australian grid, and design a micro grid to meet the power needs and quality of the area. Thirdly, to simulate different control strategies for the designed micro grid, while the micro grid, MG, is in grid-connected mode and isolated mode for different levels of PV penetration, and assessing which strategy provides the best power reliability and helps main grid performance. Lastly, to evaluate the overall results of the Power Factory simulations and judge against the standard methods of grid control, to assess if there can be an approach towards standardization.

1.2 Thesis Structure

In the following chapters, I will firstly explore the background and electrical power context of my case study (Kalbarri), the current state of the Western Australian Power Grid and the future expectations in the integration of Renewable Energy Sources into the main power industry. This chapter will be mainly focussed on the condition of the grid and the problems at hand, as well as the current degree of integration of RESs.

In the third chapter, I will discuss Micro-grids in detail, including what defines them and their development, and also what current challenges are faced by Micro-grids today.

Chapter 4 outlines the Control types and strategies, going from a generalised to more in depth description of the methods used and how they are used.

2 BACKGROUND

The secure delivery of power supply is essential for economic and social growth in modern society. Unfortunately the current infrastructure is unable to cope with increasing load demands, and struggles with integrating new technologies.

Closer to home, we are faced with many issues in power distribution in Western Australia: ageing infrastructure, increased load and limited resources such as gas and coal. Also future power delivery must take into account the Renewable Energy Target, which aims to have the country running on 20% renewable energy by 2020[1][5].

Future electricity and distribution networks have to seamlessly accommodate changes in technology, the environment, society and the economy. By having this outlook, the goals of power quality, cost of supply and energy efficiency have to be examined and optimized in new ways to accommodate changing requirements in today's market.

Already some distribution grids have bi – directional power flows made possible by dynamic control techniques, which can ease the incorporation of Renewable Energy Sources. RESs can be further integrated by using Micro-grids.

With an outlook of significant investment to renew and develop the current infrastructure, Micro grids are becoming a more viable solution for power grid quality and reliability.

2.1 Case Study – Kalbarri

Kalbarri's main district is located at the end of a 136km distribution line, at the northern border of Western Power's main grid in Western Australia. The Kalbarri electrical network is supported by an incoming 33kV feeder from the Geraldton Substation. At the end of this line four 33/6.6kV Step down transformers supply the Kalbarri Town site with 6.6kV power [Sakshi Priya, Graduate Engineer, Western Power]. Kalbarri Wind Farm was installed and operating in April 2008, consisting of two inverter- connected ENERCON E-48 wind turbine generators, rated at 800kW each [33].

Kalbarri is part of the Northern Wheatbelt Area, in Country North Region, where networks mainly consist of overhead long lines with light loads. Unfortunately this area is constrained by these long line distances in regard to voltage requirements in the power transfer from substations to customer loads. Western Power hopes to reinforce the line capacities in the Kalbarri to Northampton region, and is considering the installation of a Static Reactive Power Compensator (STATCOM) on the Northampton distribution line by 2018 [22].

Kalbarri is a centre for tourism and goes from approximately 1500 permanent residents to 8000 people in the tourist season, which causes a great strain on the electrical grid, made worse by the fact that the town site is end-of-line. So there is a long history of outages that not only effects the lifestyle of the residents but also local businesses during peak season. On 25th of March 2010, a report was made to the Minister of Energy about the frequency of the outages in Kalbarri and Northampton: between 1st of December 2008 and 28th of February 2010, 74 outages had been counted [17].

2.2 Current Issues facing the Western Australian Power grid

The main challenge for the Western Australian electrical network is the ageing infrastructure which supplies power to residential, industrial and commercial customers. There has been too little investment in the improvement of the current transmission and distribution systems. Due to lack thereof, much of the network has worked for more than 30 years, with a lifespan between 30 and 50 years, resulting in the higher likelihood of faults and serious defects. Risk of personal injury and increases in interruptions are too likely to happen with deteriorating infrastructure, so Western Power has focussed on improving the main grid. But due to the substantial investment needed for updating the entire power grid, maintenance of current assets & replacement in problem areas have received the most attention [24].

Another issue is dealing with the fluctuating load demand during the day and in the long term future predictions. The main network has to have the capacity to deal with peak demand, and Western Australia has greater differences in peak demand and average demand than other states. This is mainly due to climate (air conditioning usage), and relatively lower levels of industrial electricity users, reducing the demand for consistent use of high levels of electricity. Due to increasing electricity tariffs and unforeseen future developments in the market, peak demand and therefore capacity is hard to predict, which also means it is harder to plan for. However, the cost to accommodate this inconsistent peak load is too high to be considered economical in regards to the relative electricity usage through this time. Reducing the peak demand is therefore a more economical and efficient way to improve the system, but involves the active interaction of the residential users [23] [24].

2.3 Integration of Renewable Energy Sources

Due to increased encouragement for Renewable Energy use, Western Australia has tried to increase its renewable output within the main grid. Facing issues such as voltage control of large renewable resources, overloading of lines due to bi – directional flows, and inefficient use of residential renewables has limited this process [5].

Such challenges have made Western Power stipulate limitations such as no inverter renewable sources over 30kVA, as well as additional costs in protection usage, and bi directional meter installations. For a full system to cover peak hour use as well, battery storage is required, which usually costs more than the rest of the system put together [22].

A utility run micro grid could change the way residents and the power utility interact, having the best solution of reliability as well as household consumption responsibility, with the utilities providing the technical support the customers don’t have, so increasing the safety of renewable energy maintenance and responses to faults [1].

3 MICRO-GRID CONCEPT

The Micro- grid idea has the potential to increase the performance of power systems, by helping the integration of distributed generation and renewable energy sources, reducing overall system losses generated by long distance distribution, and increasing the reliability of electrical supply to customers [30].

3.1 Micro-grid Definition

Micro-grids are formed when a local electrical region is capable of being powered on and off the main power network. For this to occur a number of conditions must be met; such as, typically, low voltage distribution systems within, and control for efficient interaction between the main network and micro-grid. Distributed Energy Sources are a given, since it has to operate in off-grid or 'islanding' mode, which are located in the local area. These may consist of a combination of renewable energy resources, generators and energy storage. The distinctive feature of a micro-grid is the implementation of specified control, compared to electrical networks with Distributed Energy Sources (DES) controlled by the central control entity, commonly known as a Virtual Power Plant. Micro-grids do not include Virtual Power Plants operating in cross-regional setups, since they aren't typically physically located nearby to local consumer loads and act as a power source to the entire grid [1][12].

Thus, the micro-grid is a concept that assists in the participation of both supply-side and demand-side resources, and offers flexibility for future uses. It is a model that also reduces the demand for distribution and transmission facilities, looking from a utility point of view.

3.2 Development of Micro-grid Design

Requirements of Micro-grid design aim for efficient and reliable power distribution in grid- connected and islanding modes. The fulfilment of these requirements largely depends on the site requirements and use of DESs.

Implementing a micro-grid requires an in-depth knowledge of current/possible load profiles and the types of DESs used in its design, to produce effective control strategies, first in the micro-grid voltage and frequency regulations and second in the power transfer with the main network. The nature of the micro-grid (AC, DC or Hybrid) is decided when load profiles are fulfilled by the particular DESs, like Renewable or AC generators, along with cost of equipment versus losses.

An example of a typical micro-grid design, proposed by CERTS, is shown in Figure 1. From the main grid control side, the entire micro grid would appear as a single load, connected via the Point of Common Coupling (PCC). This PCC is on the primary side of the transformer and is a switch device between the grid and the micro-grid. This makes certain the smooth cross over from grid-connected to islanded mode. As seen in the Figure, Feeder A & B are reserved for ‘sensitive’ loads which means they are the most important and need the most steady amount of power transfer. Located on these two feeders are the Micro sources, or DESs, which supply power firstly to the sensitive loads and then to the traditional loads on Feeder C. As an addition in Feeder B, a Cooling Heating and Power sources supplies both heat and power to the load.

If a fault is detected in the main grid, the Micro-grid can island itself. If there is not enough energy in the Micro-grid for all the loads, it powers the sensitive loads while cutting off Feeder C using the Separation Device (SD). This just means that the traditional loads are left to ride through the main grid fault. Both the PCC & SD will reconnect once the fault has been resolved, and reset the system for operation in grid-connected mode [8].

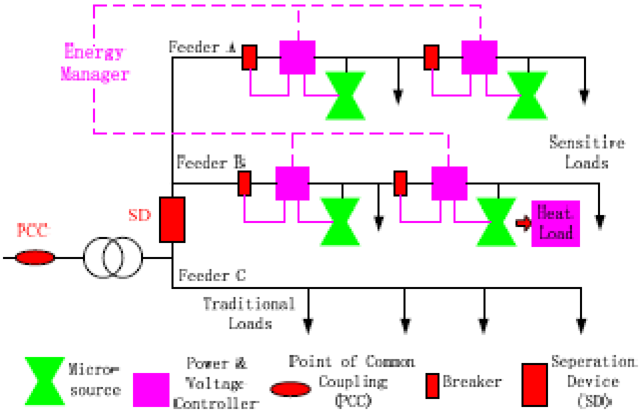


Figure 1. Basic structure of micro grid [8]

Due to the use of multiple DESs in the micro-grid, protection grading and reach must be extensively investigated. However the amount and type of protection depends on loads and DES types and control. Protection has to detect and quickly respond to main grid and micro-grid faults. This may mean isolating the micro-grid from main grid faults or protecting DESs within the micro-grid from its own faults. Main grid distribution protection is based mostly on short circuit current sensing, however due to the integration of DES units in the micro-grid, the change in direction and/or magnitude of certain fault currents may present protection failures in certain circumstances [11][29].

3.3 Challenges in the Integration of Micro grids

In the creation of Micro grids, various challenges are clearly seen due to its very nature.

One of the main challenges is transitioning from Reactive and Power Factor control in grid connected mode to isolated mode, where micro grid control is interrupted and the main grid has a drastic reduction in load.

Also establishing micro grids require a different relationship between the power utilities and customers called Demand side Integration; where customers take an invested interest in the power distribution in their own area and the utilities help facilitate their needs. Currently the relationship between utilities and customers is very one- sided, since most electricity is produced by the utilities.

Integrating Decentralized Energy Sources create bi–directional power flows that the current grid is unable to handle, and requires upgrading to an entirely different kind of protection coordination, voltage control and fault current detection.

With the increase in control units in the Micro grid, as well as distributed generation, electronic equipment can cause severe frequency deviations in isolated mode if the right control parameters aren’t specified. Also it will be necessary to take into account the communication between different sources if uncertain parameters like the load profile and weather conditions change rapidly.

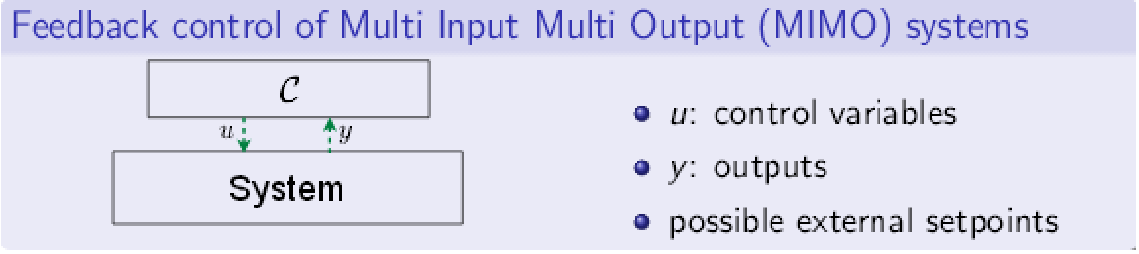
With the integration of renewable sources, better storage and battery technology needs to be improved in technical and economical areas. Battery storage improves general operation of micro grids in regards to normal load and supply changes as well as when changing from grid connected mode to isolated mode [1], [3], [5], [18], [19], [28].

4 CONTROL STRATEGIES

4.1 Types of Control Methods

4.1.1 Centralized Control

Centralized control concentrates on optimization objectives within the grid, which is based on existing energy management systems. This kind of controller generally requires a user interface to react to certain transient circumstances [1] [4] [14]. Figure 2 explains the feedback loop of the control system, where all variables are sent to the system, and all outputs processed via one controller. This makes a complex system configuration the bigger the system gets.



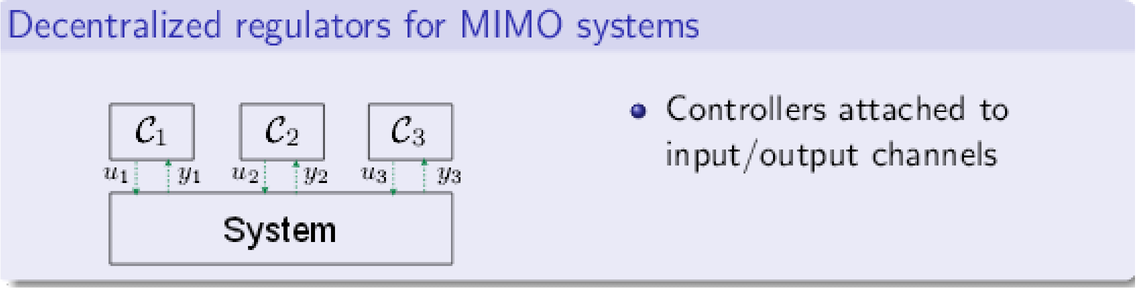
Feedback control of Multi Input Multi Output (MIMO) systems

- u: control variables
- y: outputs
- possible external setpoints

Figure 2. Control diagram for Centralized System [8]

4.1.2 Decentralized Control

Decentralized control is an automated way of managing information, and can react immediately to local disturbances and problems, with multiple controllers contributing to system reliability and quality, but the lack of communication between controllers limit the system’s efficiency [1] [4] [14].

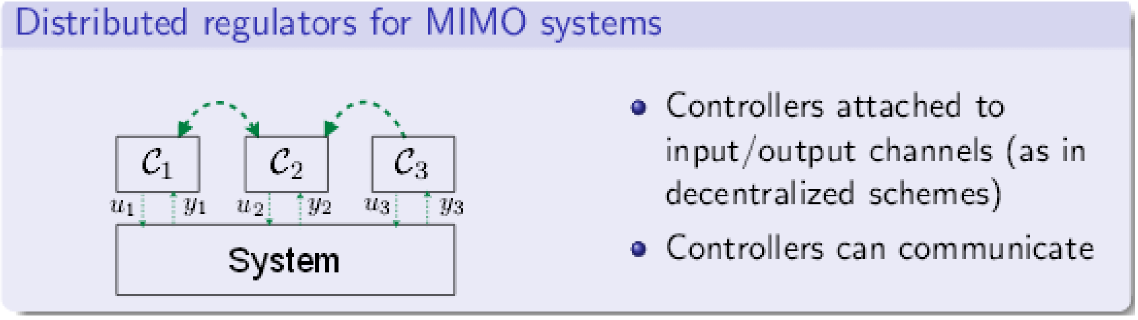

Decentralized regulators for MIMO systems

- Controllers attached to input/output channels

Figure 3. Control diagram for decentralized system [8]

4.1.3 Distributed Control

Distributed control is a more developed method of decentralized control. However in this type of system, multiple controllers depend on communication between each other to fulfil input/ output requirements. A typical example of this type of control is the Multi- Agent system, where each agent has its own set of control objectives and is not controlled by external commands. The level of communication for this system adapts to unreliable sources of energy like solar and wind [4].


Distributed regulators for MIMO systems

- Controllers attached to input/output channels (as in decentralized schemes)
- Controllers can communicate

Figure 4. Control Diagram for Distributed System [6]

4.2 Distributed Generation Control

The basis of control strategies can be described in equation form. Below shows the equations for power transmission through a lossless line;

$$P = \frac{V_1 V_2}{X} \sin\delta \quad , \quad Q = \frac{V_2}{X}(V_2 - V_1 \cos\delta)$$

The above equation is displaying the relationship between power, voltage and reactance (In a lossless line, resistance is not considered), where P is active power and Q is reactive power. V_1 and V_2 represent the voltage at each end of this line, X is the reactance and δ is the power angle. Since the power angle, the angle between the voltage at each end of the line, is quite small, the equations above can be further simplified to create the equations below;

$$\delta \approx \frac{PX}{V_1 V_2} \quad , \quad (V_2 - V_1) \approx \frac{QX}{V_2}$$

This shows that the power angle and the voltage differences are directly proportional to the Active and Reactive power, respectively.

4.2.1 PQ Control

The objective of PQ control is to maintain the level of active and reactive power at set reference points. As described below in Figure 5, voltage and frequency are used to ensure the Micro grid's active and reactive power standards are maintained [8] [2].

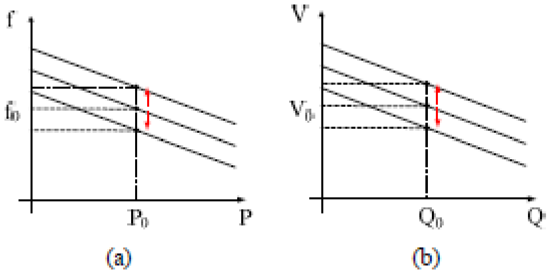


Figure 5. Theory of PQ Control (a) Frequency droop characteristic (b) voltage droop characteristic [8]

This is a more efficient use of a control strategy, optimising power output but at the cost of a stable voltage and frequency control. It is therefore referred to as a current controller [31].

4.2.2 Droop Control

Droop control refers to the main frequency regulation of the typical power system. This method uses the linear relationships of active power/ frequency and reactive power/ voltage, as seen in Figure 6. This kind of control has limits instead of set points for voltage/ frequency and active/reactive power, and acts to put the surrounding system in equilibrium by shifting points on that linear relationship. In micro grid applications it can act to share load demand according to droop characteristics in an islanding situation. Unfortunately as a consequence this means the micro grid cannot reset to the original main grid frequency, and may affect certain micro grid equipment upon reconnection to the main grid [2] [8].

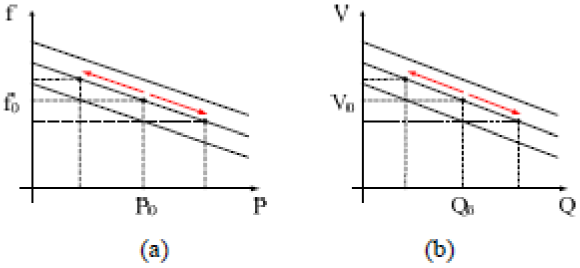


Figure 6. Theory of Droop Control (a) Frequency droop characteristic (b) voltage droop characteristic [8]

Since it has a linear relationship, with the input of two variables, it is used in centralised systems to balance the control of two opposing control units [31].

4.2.3 V/f Control

For V/f Control, the controller acts as a voltage source, maintaining voltage amplitude and frequency through injecting active and reactive power as seen in Figure 7 [2] [8].

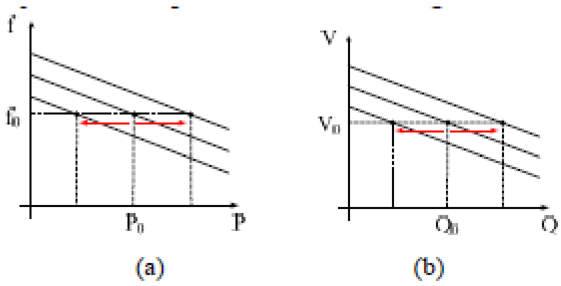


Figure 7. Theory of V/f Control (a) Frequency droop characteristic (b) voltage droop characteristic [8]

So rather than prioritising to the power efficiency, it concentrates on maintaining the voltage and frequency, and concentrates on system reliability at the expense of extra power. These are commonly used in isolated mode but are commonly disconnected in grid connected scenario as it counters the grid control [1].

4.3 Hierarchical control vs Master – Slave control

4.3.1 Hierarchical Control

Control of a micro-grid can be broken down into three Hierarchical control levels. The first is primary control which focusses on local/ internal control of the micro-grid. This is based on local measurements and no communication is required; therefore islanding detection, power sharing, and output control are included in this category.

Secondary control or micro-grid Energy Management System concentrates on the power supply in grid connected and islanding modes. Its purpose is finding the optimal Unit Commitment in each mode and communicates with the DESs to see that selected goals are attained, and also voltage and frequency deviations from Primary control are corrected. This is where decentralized hierarchal control and real time systems are used.

Tertiary control sets long term objectives depending on the main power system. This involves (if applicable) the communication between multiple micro-grids and the main grid and/or the main grid and the micro-grid [7] [19].

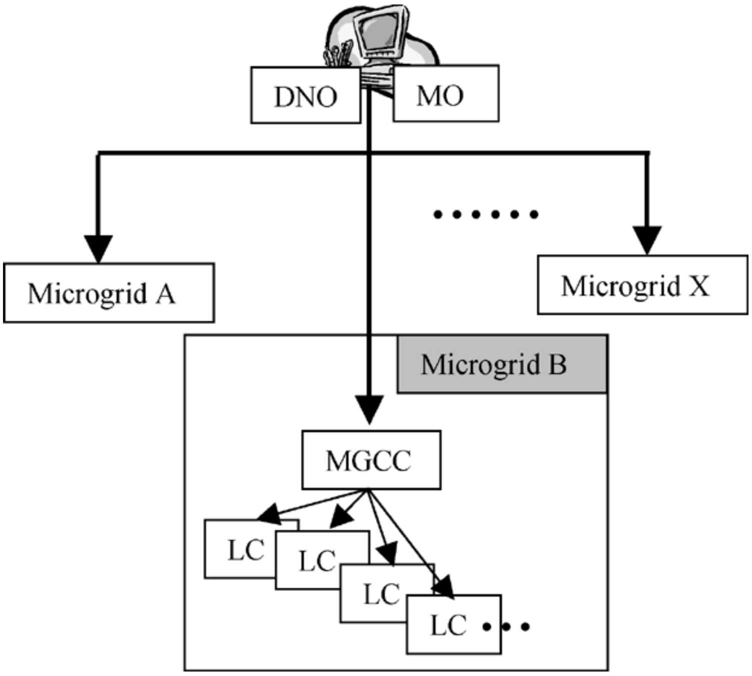


Figure 8. Control levels of the micro grid environment [4]

4.3.2 Master - Slave Control

For a Micro grid control system with one (or more) master controller(s), V/f control is used to set the original voltage for islanded control. This master controller(s) acts to preserve the system frequency while the other controllers are set to PQ control. When the system changes to grid – connected mode, all controllers can be set to PQ control for higher performance. Therefore only the master distributed generator changes between these two modes [2]. It also makes it easier to add extensions onto the grid, as the control of the different sources seamlessly integrate with one another.

4.4 Standardization of Micro grid Control

As the Micro grid concept varies from different conditions and design, so do the control strategies. While typical Master – Slave control works on the assumption of unnoticeable connection to the grid, this project will explore the positive contributions different types of Master – Slave control strategies have and the effects produced by the different Master – Slave relations [31].

5 POWER FACTORY SIMULATIONS – KALBARRI

5.1 Introduction

The purpose of these simulations is to replicate the conditions of a Master – Slave control strategy in the Case Study of a Kalbarri Micro grid, consisting of two of the four main feeders, and compare the options of the Master control such as PQ, Droop and Vf control in grid connected mode.

I designed the Kalbarri micro grid for the purpose of simulating an area with residential photovoltaic systems, and the improvement that control can have on the main grid as well as the local area. This also shows the benefits of utilising local energy sources, and compromising with residents for sustainability and voltage reliability that the Kalbarri line is currently struggling with.

Essentially, PQ control represents the normal function of a grid without control (most inverters are set for maximum efficiency), or the passive control that most Master – Slave micro grids default to in grid –connected mode. This default is recommended so the micro grid has no effect on main grid control; however the situation in Kalbarri is different due to its end-of-line location.

With this in mind, I simulated the different types of Master control, comparing voltage reliability and efficiency, to judge which control worked best. Reliability has more of a priority, due to the fact that the losses over the system will be improved due to local generation anyway. This was done in maximum load conditions and showed the outcomes with 20%, 50%, 80% and 100% PV penetration (percentage of load covered by solar PV generation). The micro grid simulated represents less than half the loads of the Kalbarri power grid.

There are limitations in the components of the software that somewhat effect the results. The simulated PV arrays and battery system is based on a Power Factory component called a static generator. In the case of the PV arrays it acts as PV panels and control systems required, but limited by the fact it won't encompass the use of maximum power point trackers, or exhibit the inefficiency characteristics of a normal PV panel. With the battery, it incorporates a dc battery and control systems. Both are dc components but due to the models of the static generators it acts as an AC components with inbuilt inverter.

Control of the PV arrays and battery system are set by the control tab of the static generator component settings, where PQ, Vf or Droop control can be selected and according to the type of control, the associated required limitations can be fixed at a certain point. With the PV arrays, they were all set to PQ control and the limitations were set according to the percentage of PV penetration necessary for that particular simulation. The battery system acted as the master control and was simulated with the types of control according to it 1MW limit and voltage/ frequency limits.

5.2 Base Case

As shown in the following figures, the main issue for Kalbarri power reliability is the long distance line feeder from the Geraldton Substation. According to the Power Factory Simulation provided by Western Power, the only low voltage bus readings are on the High Voltage side as seen in Figures 9 & 11. Figure 9 shows the components at the Kalbarri Substation, with two 33/6.6kV transformers, and four main distribution feeders leading to the rest of Kalbarri. Figure 10 & 11 shows this substation in the context of the low voltage grid, before and after a power flow analysis is done. This describes the fact that the only low voltage seen is the end of the Geraldton distribution feeder coming into the Kalbarri Substation, with the transformers optimized to keep the 6.6kV side in the voltage limits.

Overloaded lines are present in the feeder coming from Geraldton (Figure 12), as well as the Grey St feeder from the Kalbarri substation (Figure 11). Figure 12 is the start of the Geraldton distribution feeder, and current line infrastructure overloaded at full load, without any added extensions. The Power consumption for the Kalbarri grid was 6.71MW.

A Voltage Profile in Figure 14 also displays the variation in voltage of the 136km 33kV feeder providing Kalbarri with power. The spikes of increasing voltage in this diagram are the effects of 3 200A single phase voltage regulating transformers; one set at 47km, and the next at 84km from the Geraldton substation. The voltage profile displays the voltage in p.u. on the y – axis and the distance from the Geraldton substation on the x-axis. Even with the presence of the voltage regulating transformers, the voltage stills sinks below low voltage limits; going from 1.015 to 0.94 p.u repeatedly along the line. This leads to decreasing reliability and is the source of the frequent outages complained about in the Kalbarri area.

5.2.1 Power Factory Diagram

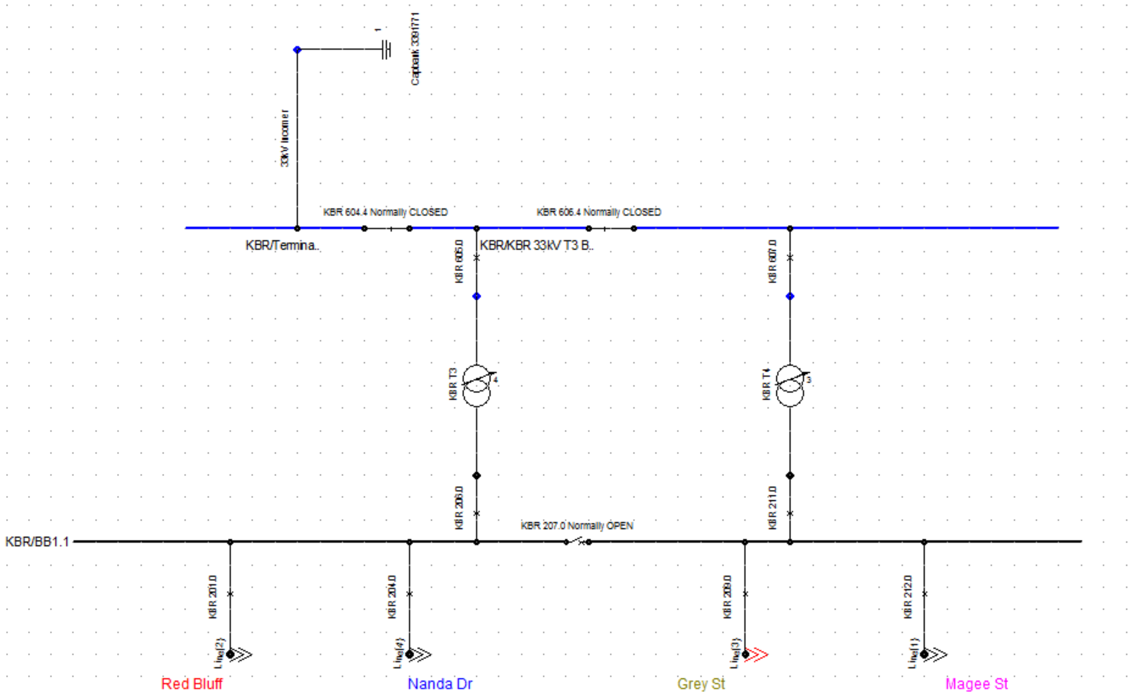


Figure 9. The start of the LV Distribution network to the Kalbarri grid

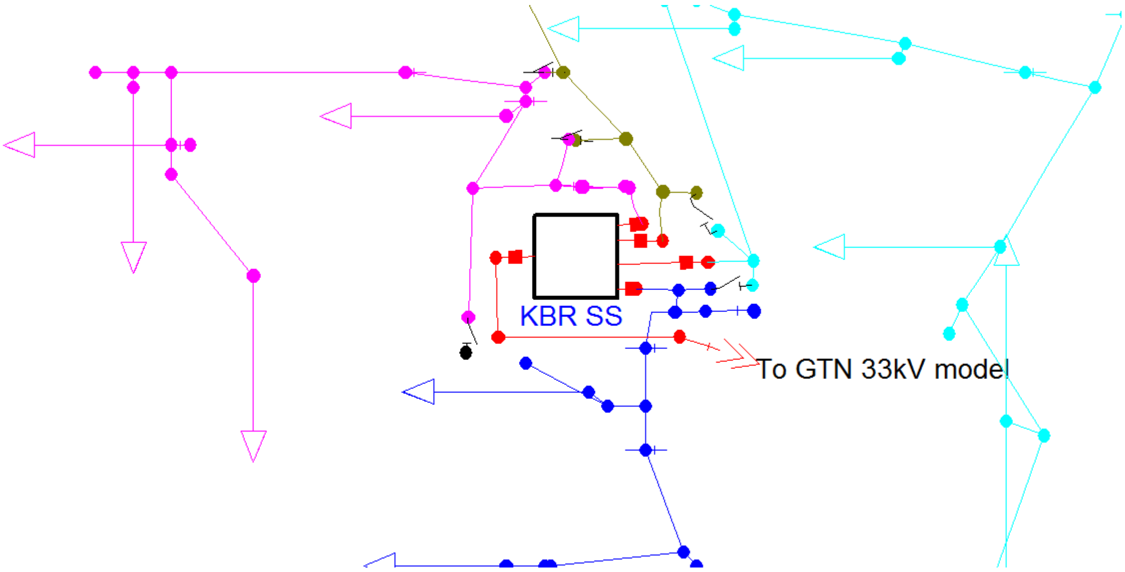


Figure 10. Kalbarri LV grid

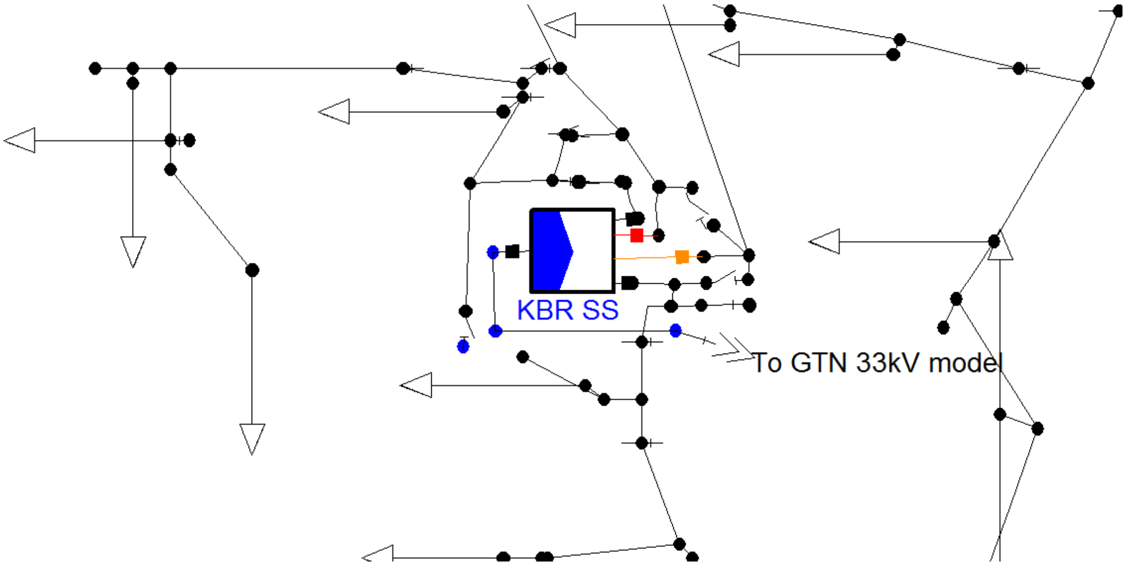


Figure 11. Kalbarri LV grid after load flow calculation, blue showing the buses with low voltage (<0.95p.u.) and potentially overloaded lines at Nanda Drive and Grey Street Feeders

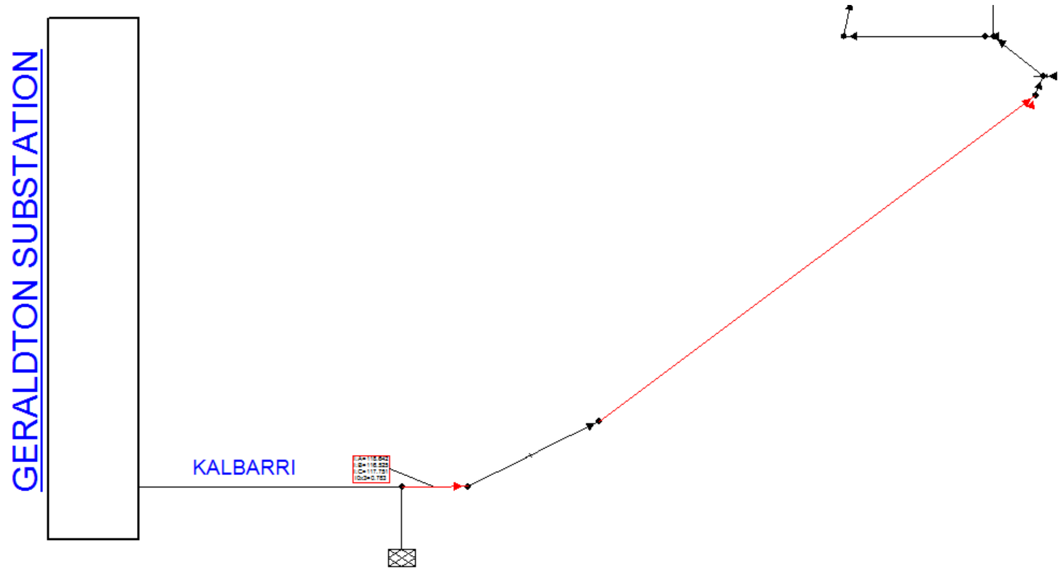


Figure 12. Feeder to Kalbarri from Geraldton Substation showing overloaded lines for the base case

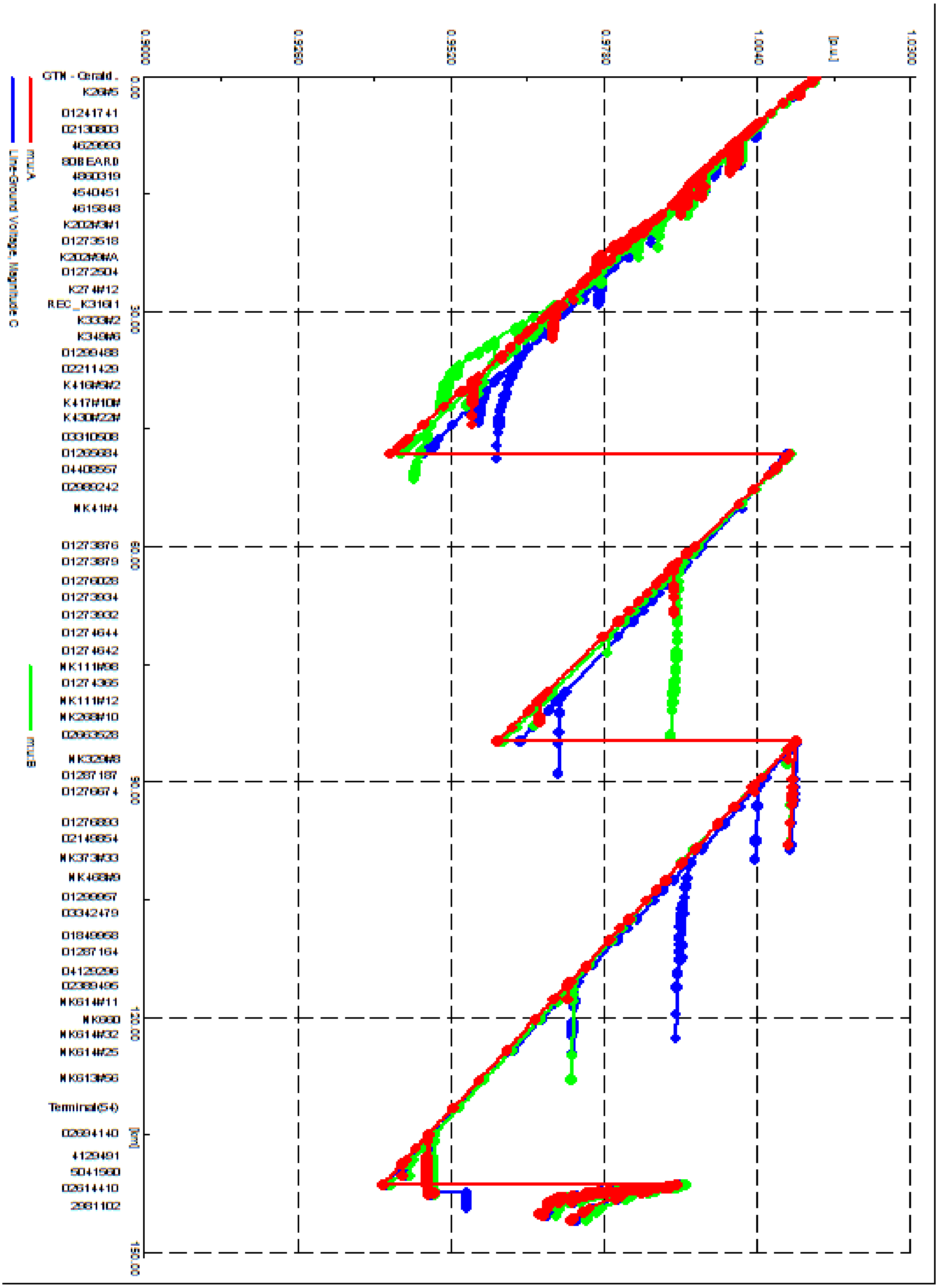


Figure 13. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Base Case

5.3 Kalbarri – Micro grid Design

The Micro grid design for Kalbarri reflects the needs and issues addressed in Chapter 2, while also introducing two very different types of Distributed Energy Sources and catering to all the different styles of control.

The design of the actual micro grid is influenced by the idea of residential input of PV arrays on household roofs. At the moment, Western Power struggles to integrate large Renewable Energy Sources into the grid, due to the large bi- directional flows, so only power sources under 30kVA are permitted from residential areas. As the designer for the proposed micro grid, my aim was to show how micro grids can improve the input from household renewable energy sources. Figure 15 shows the overall design as well as loads that represent residential areas rather than individual houses, so these arrays do fit under guidelines stated by Western Power.

The Overall design of the micro grid caters only to one side of the entire Kalbarri LV grid, making up just less than half its load, which is about 2MVA in total. The main issue with design was where to place the main power hub, consisting of a 1 MW synchronous generator and 1MVA battery energy storage system. In Grid Connected mode, if the Main power hub was too close to the Kalbarri substation, it would cause overloaded lines for the Grey St Feeder. So the switches that connected the Grey St feeder to the Magee St feeder were closed to decrease the load on these lines as well as creating a centralized location for this main hub.

The power output of this power hub provides the micro grid with reliable power in isolated mode when little to no PV is being produced. The battery storage system provides seamless transfer when connecting to and from the main grid, responds quicker to transient fluctuations and delivers power when different distributed energy sources come on and off the micro grid [2].

In Grid – connected mode, the synchronous generator was simulated to be off, simply due to the fact that it only provides power in isolated mode; when the micro grid needs the power most and to charge the battery when no extra power from solar PV sources is available.

Keep in mind that in considering Figures 16 & 17, the peak hour load, used in the Power Factory simulations, do not coincide with optimal times of PV array output. Although we can predict what happens in practice, for the purposes of this static load simulation, the PV array will be running for peak hour load.

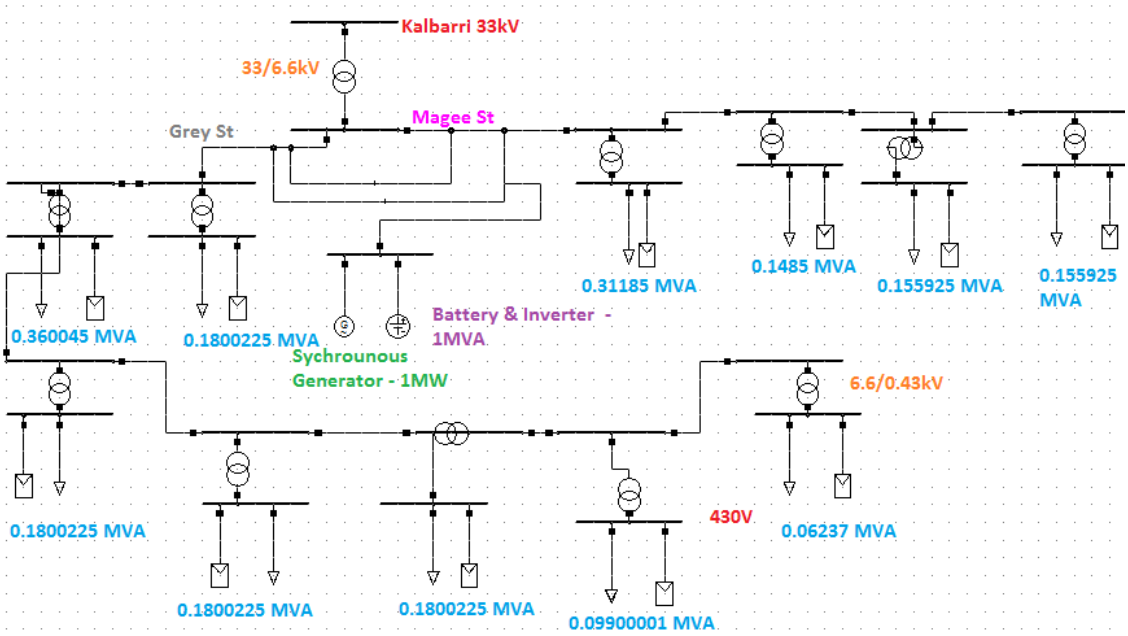


Figure 14. Kalbarri Microgrid Design

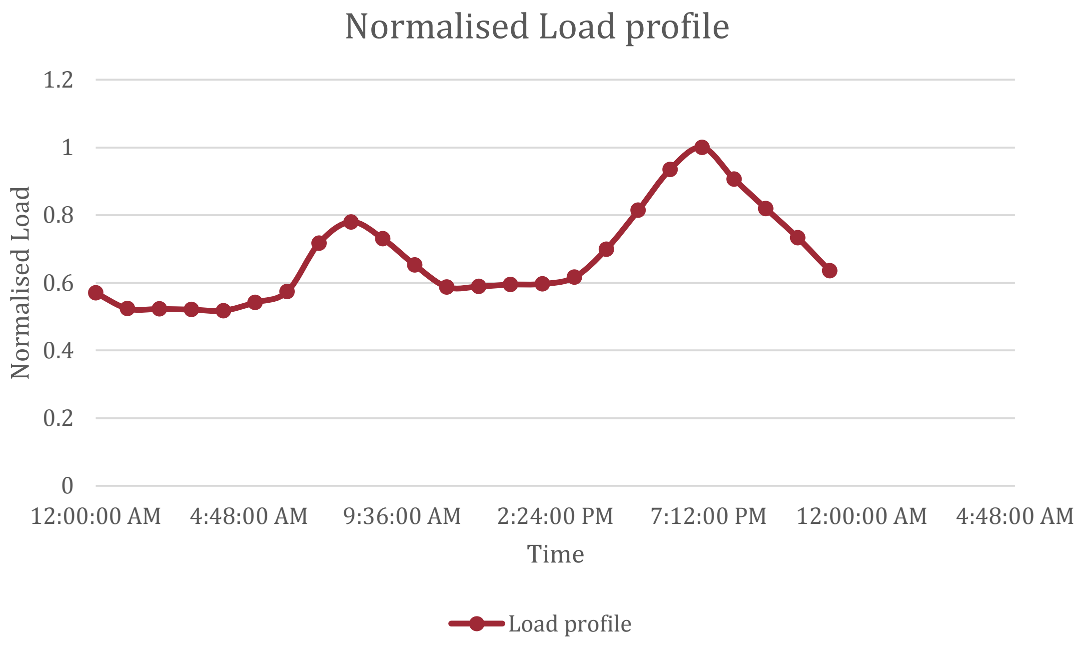


Figure 15. Normalised Load Profile for Kalbarri with main peaks at 8am and 7pm [Sakshi Priya, Western Power, 2015]

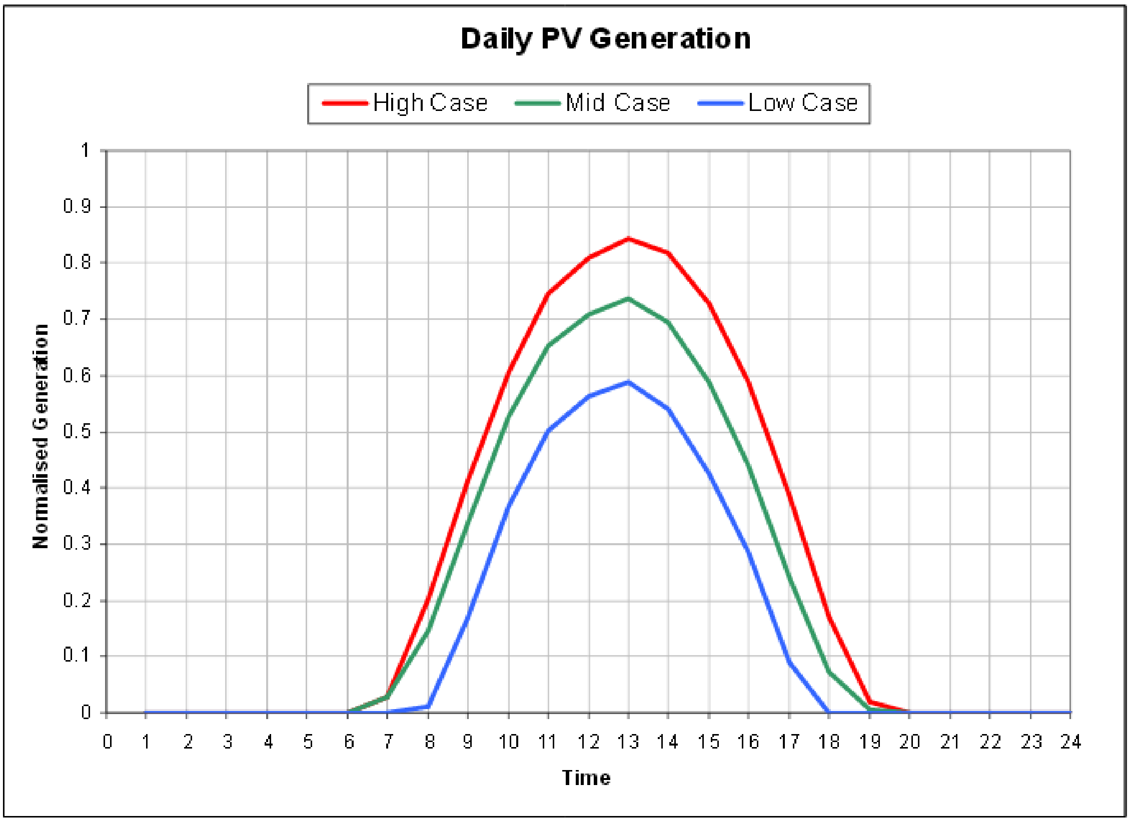


Figure 16. Normalised PV Generation average output throughout a 24 hour day per PV unit [25]

In regards to control, the Master – slave strategy will be compared in Grid connected mode with the Master being PQ, Vf or Droop Control, while the rest of the grid is efficiently optimized in PQ Control. Then reliability and efficiency will be compared in this mode.

5.4 PQ Control Simulation

5.4.1 Power Factory Grid – Connected Results

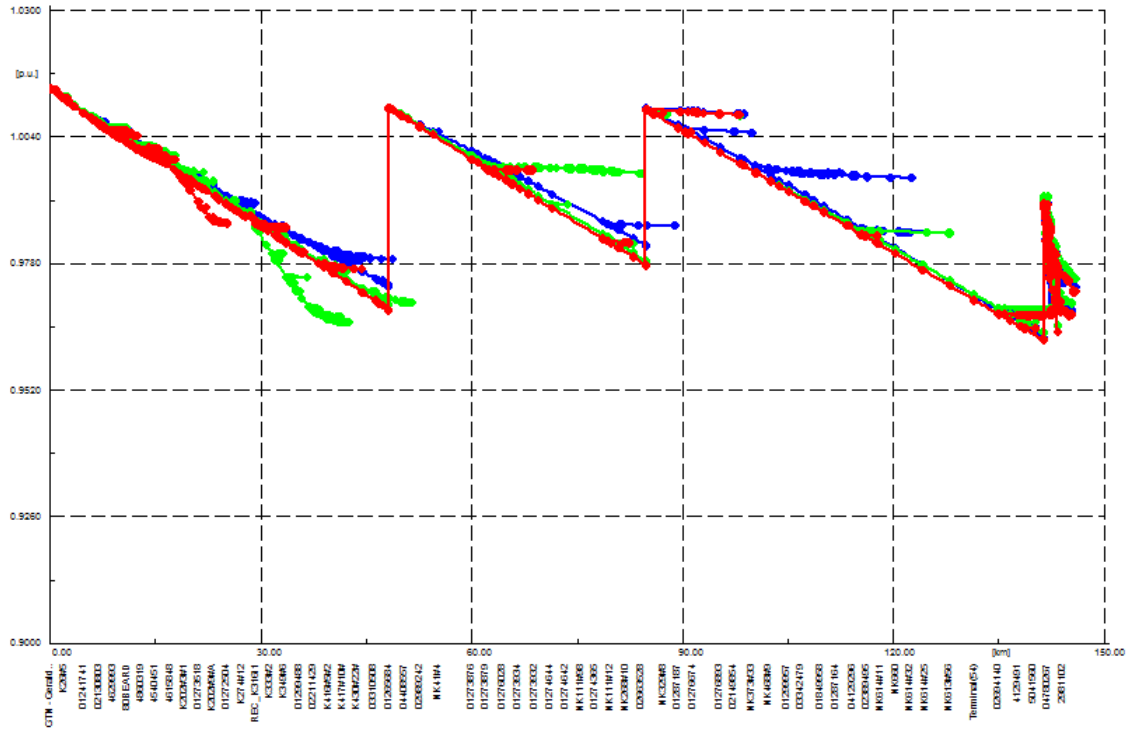


Figure 17. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- PQ Control for Grid connected mode 20 % PV penetration

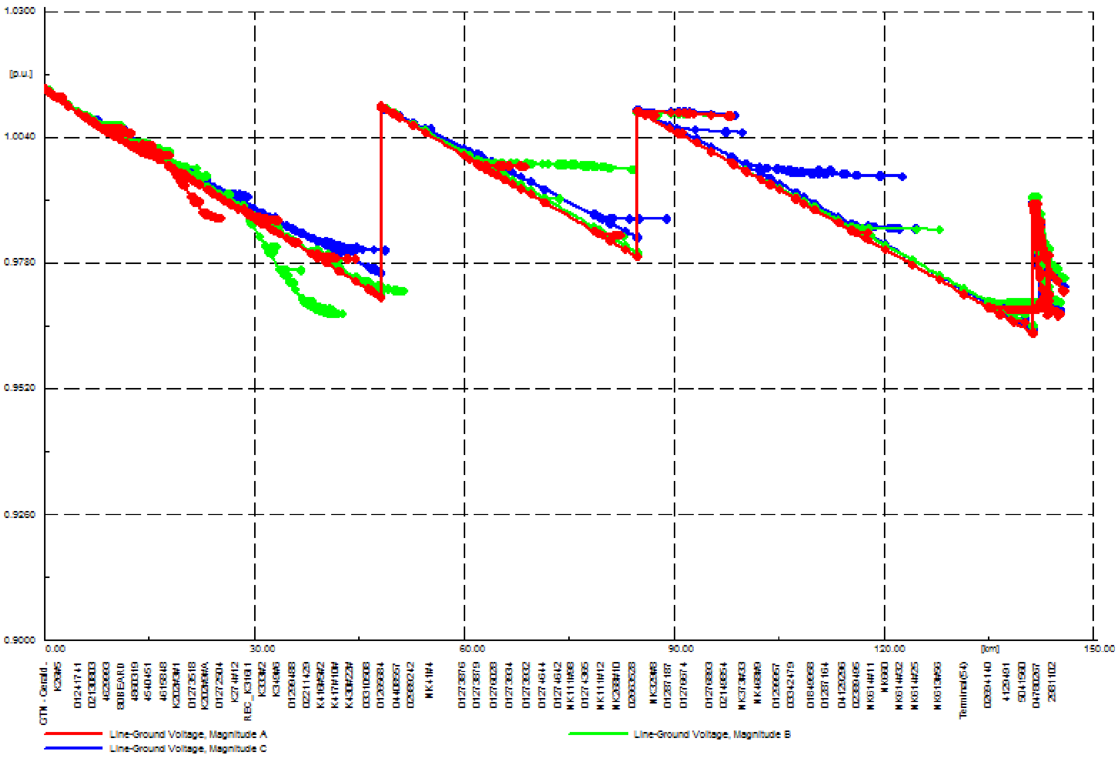


Figure 18. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- PQ Control for Grid connected mode 50 % PV penetration

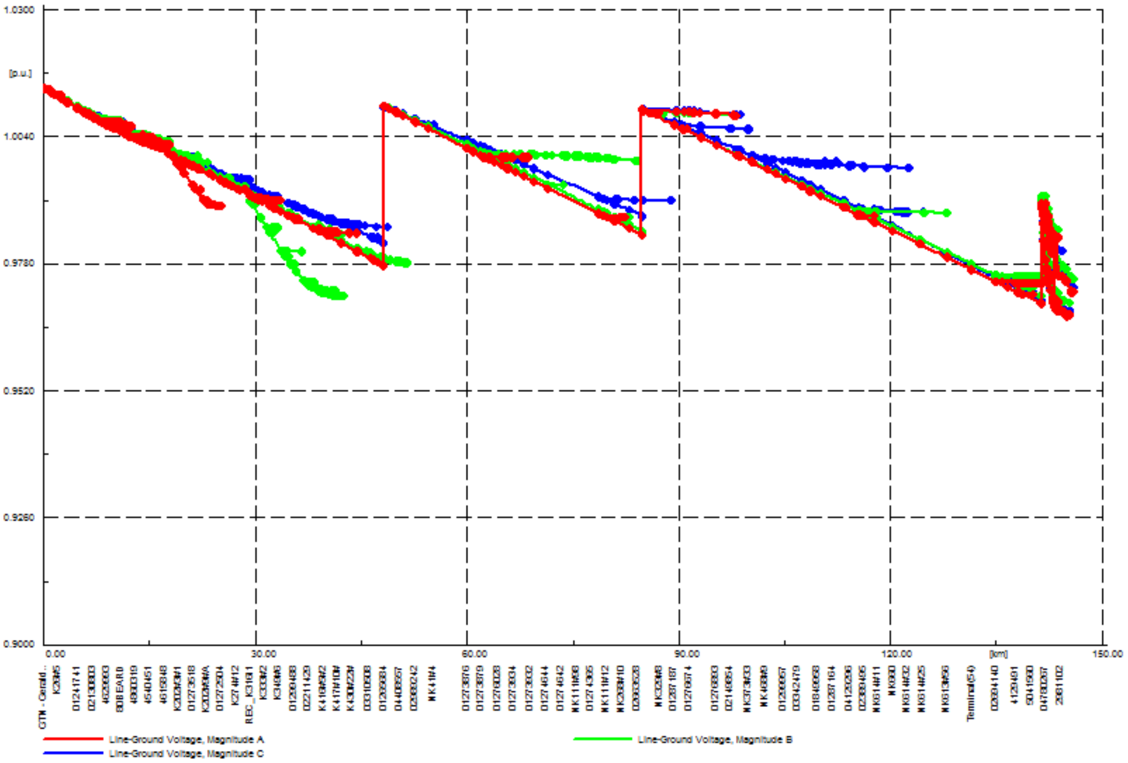


Figure 19. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- PQ Control for Grid connected mode 80 % PV penetration

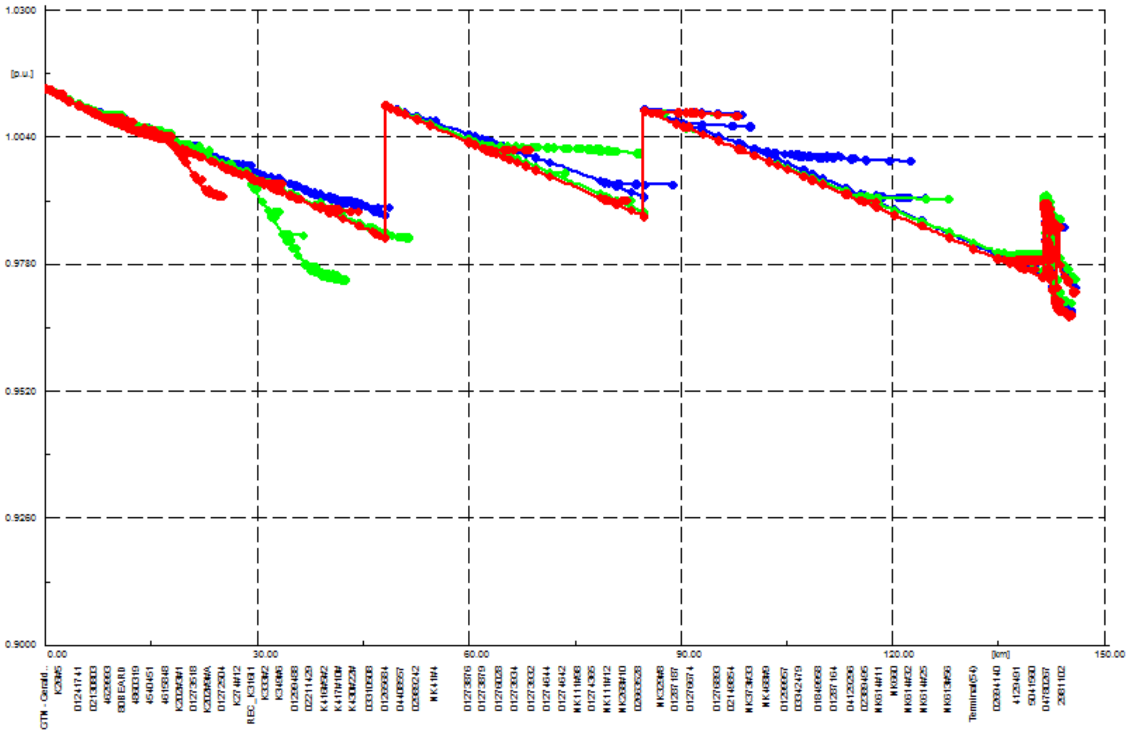


Figure 20. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- PQ Control for Grid connected mode 100 % PV penetration

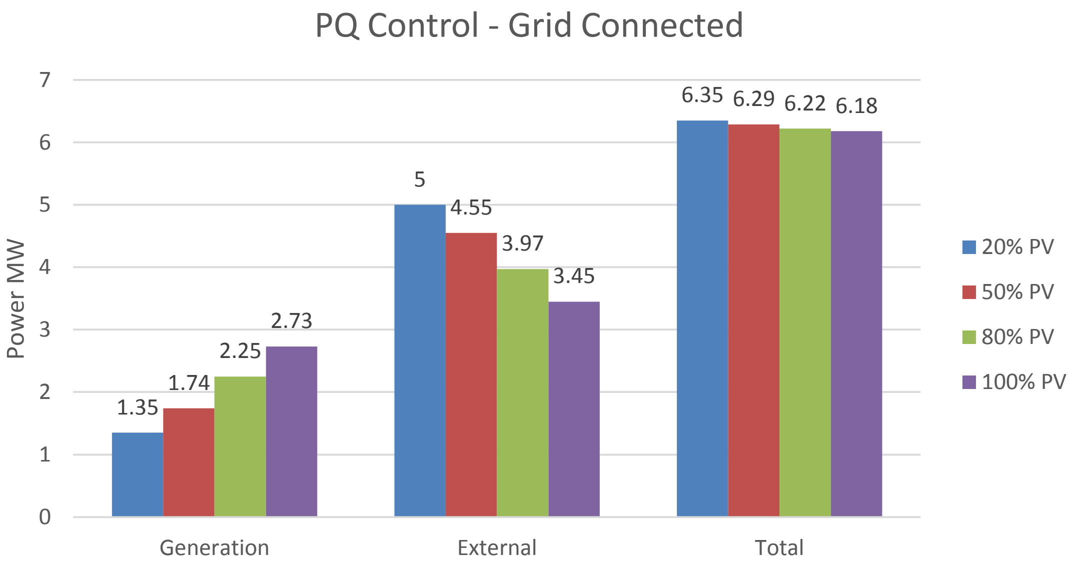


Figure 21. Power Comparisons for PV Penetration for PQ - Control

5.4.2 Discussion

The steady increase in PV penetration also increased the lowest voltage throughout the feeder, from 0.9585 p.u. at 20% PV penetration to 0.968 at 80% PV penetration; which is an improvement of 0.0095 p.u. Power Consumption was also reduced when local PV went from 20% to 80%, saving 130kW of power over the entire Kalbarri grid.

5.5 Droop Control Simulation

5.5.1 Power Factory Simulation – Grid Connected mode

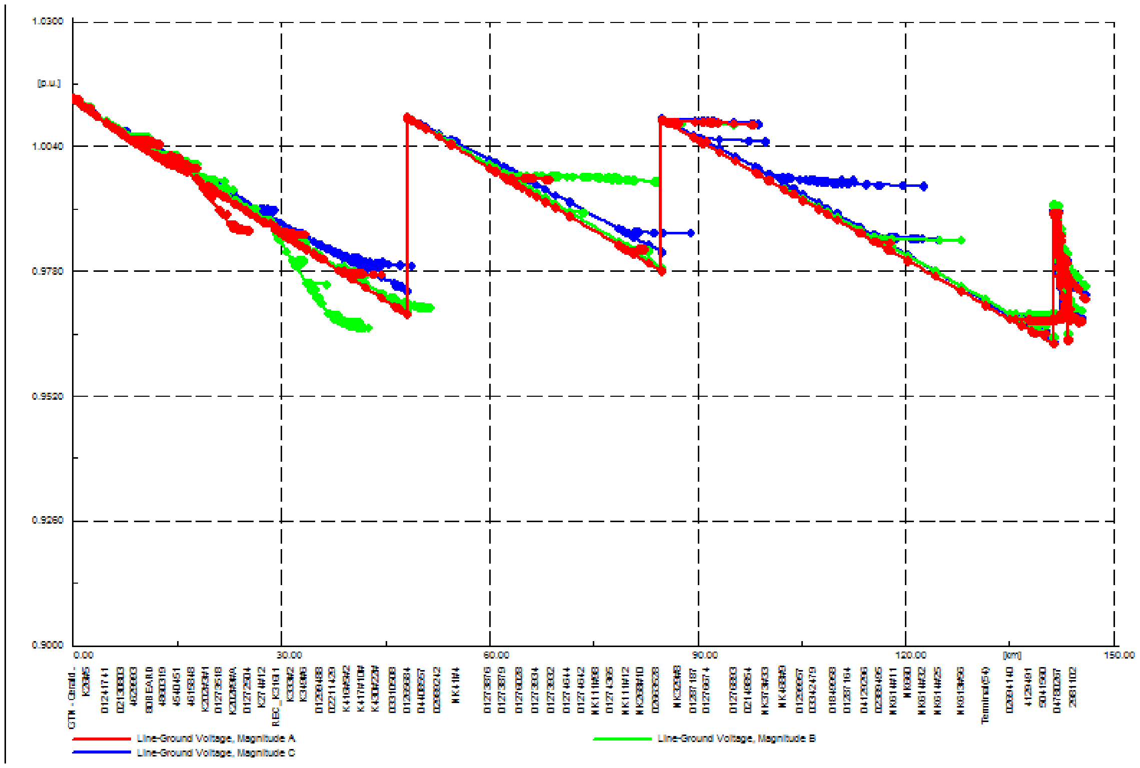


Figure 22. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Droop Control for Grid connected mode 20 % PV penetration

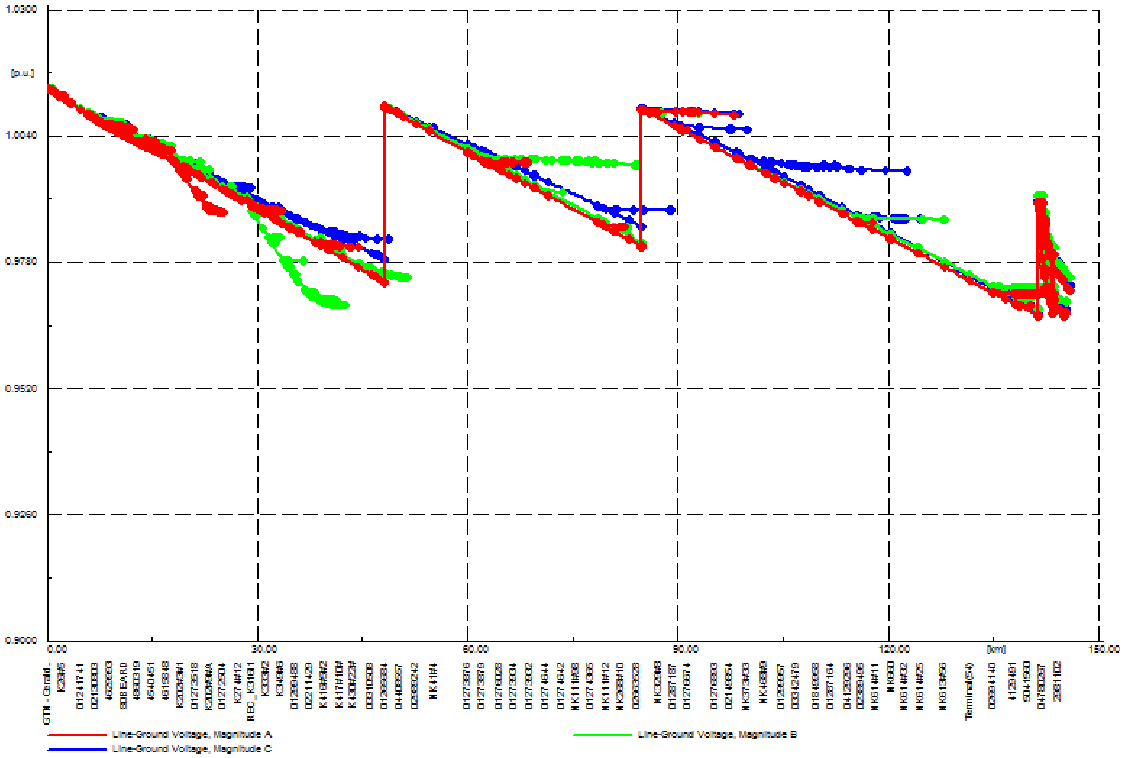


Figure 23. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Droop Control for Grid connected mode 50 % PV penetration

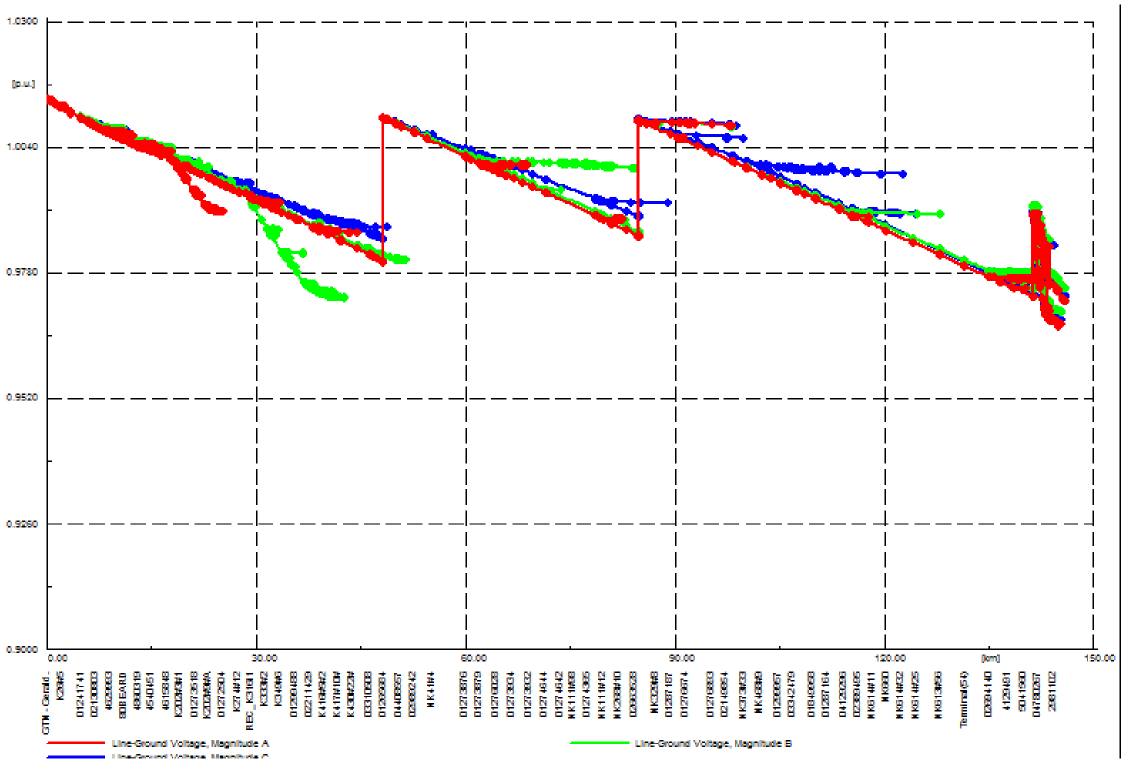


Figure 24. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Droop Control for Grid connected mode 80 % PV penetration

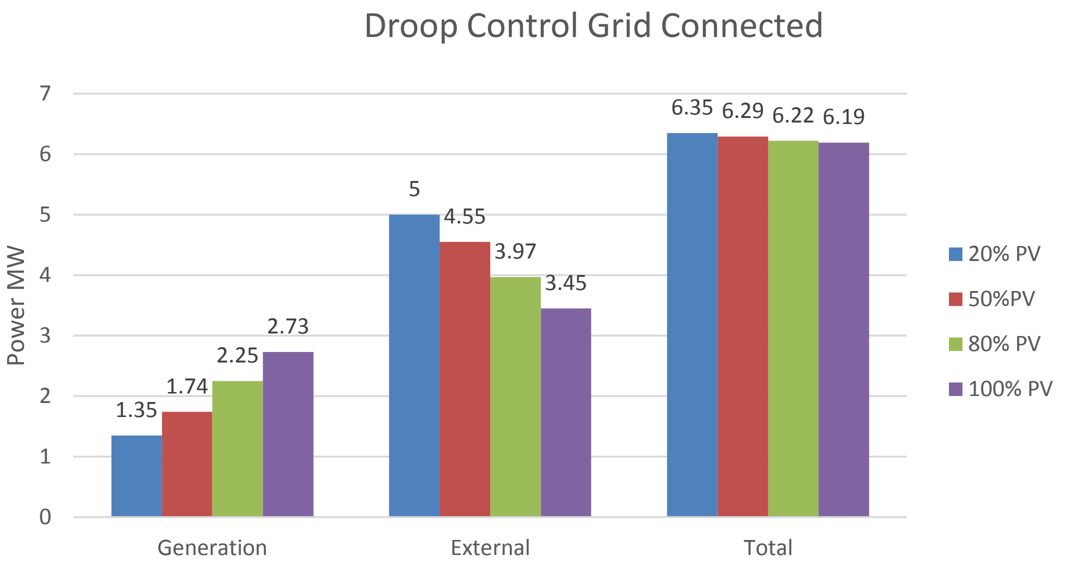


Figure 25. Power Comparisons for PV Penetration for Droop - Control

5.5.2 Discussion

The steady increase in PV penetration also increased the lowest voltage throughout the feeder, from 0.96 p.u. at 20% PV penetration to 0.969 at 80% PV penetration; which is an improvement of 0.009 p.u. Power Consumption was also reduced when local PV went from 20% to 80%, saving 130kW of power over the entire Kalbarri grid.

5.6 Vf Control Simulation

5.6.1 Power Factory Simulation – Grid Connected mode

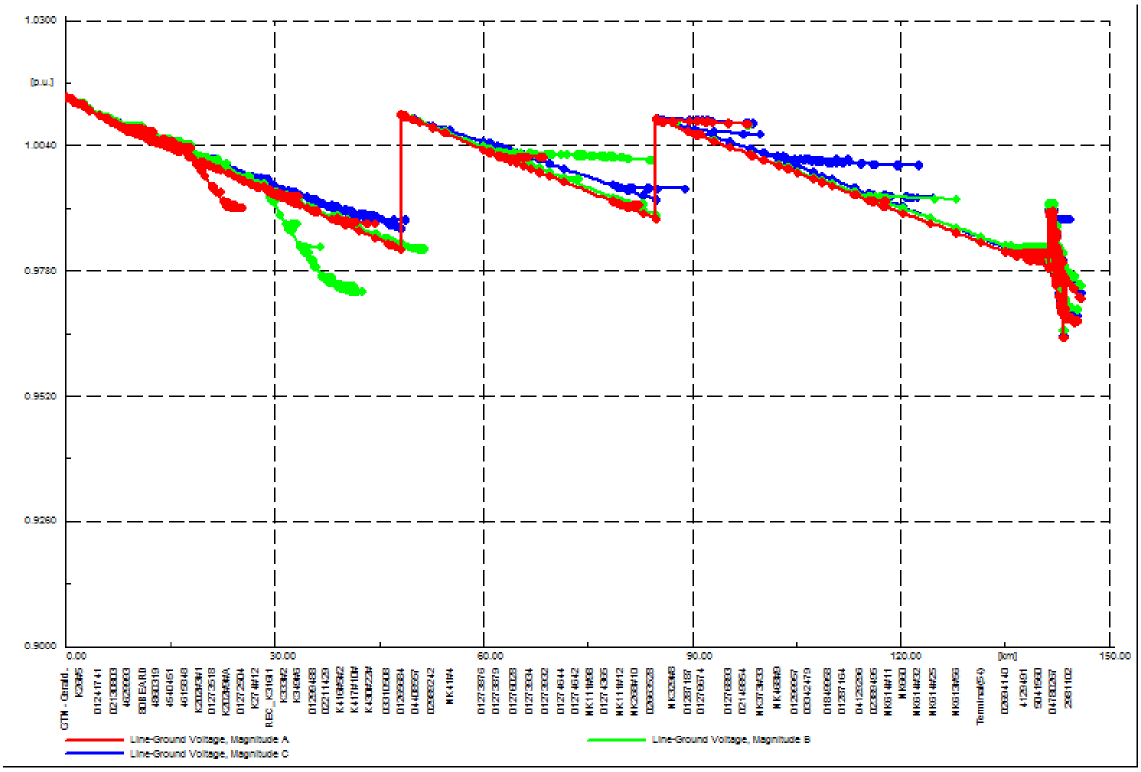


Figure 26. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Vf Control for Grid connected mode 20 % PV penetration with Overloaded battery at 128%

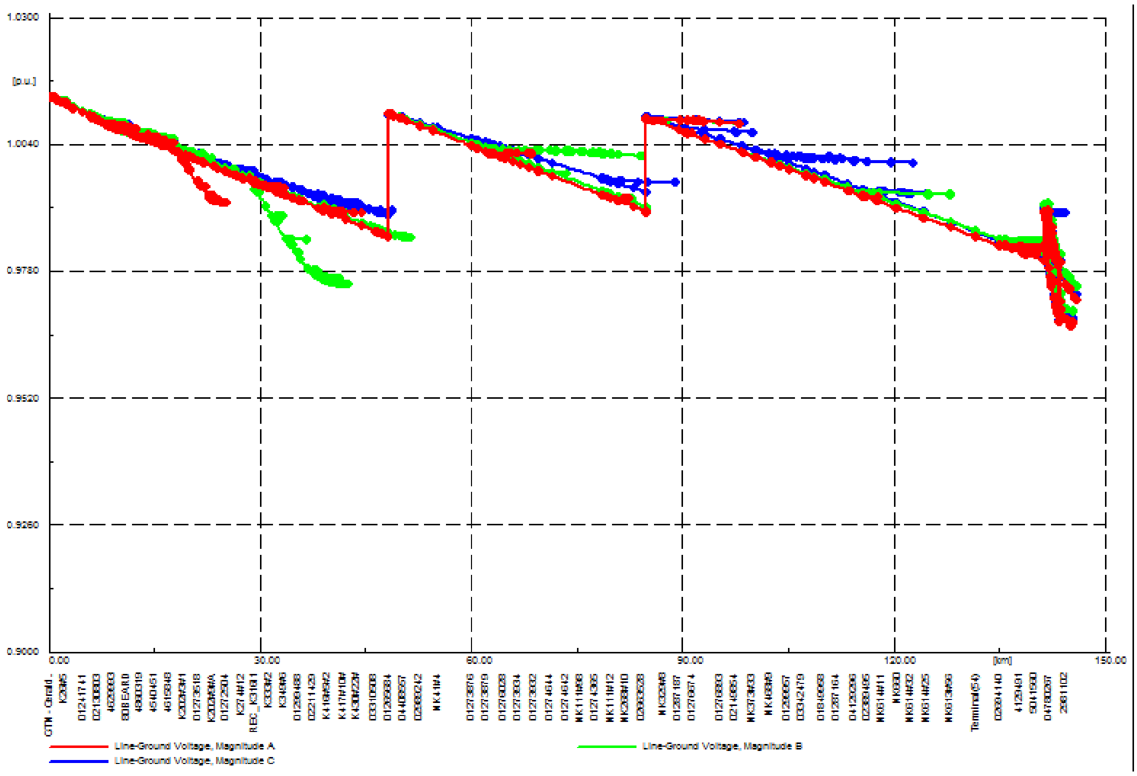


Figure 27. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Vf Control for Grid connected mode 50 % PV penetration with Overloaded battery at 138%

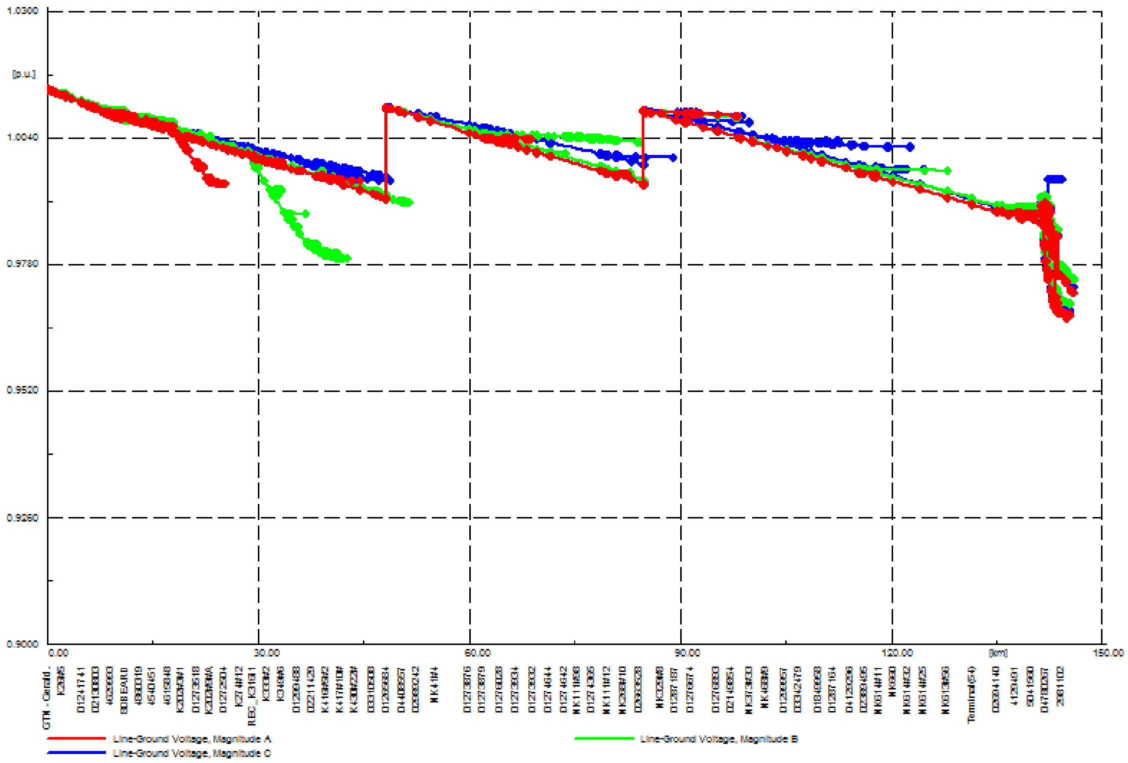


Figure 28. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Vf Control for Grid connected mode 80 % PV penetration with Overloaded battery at 138%

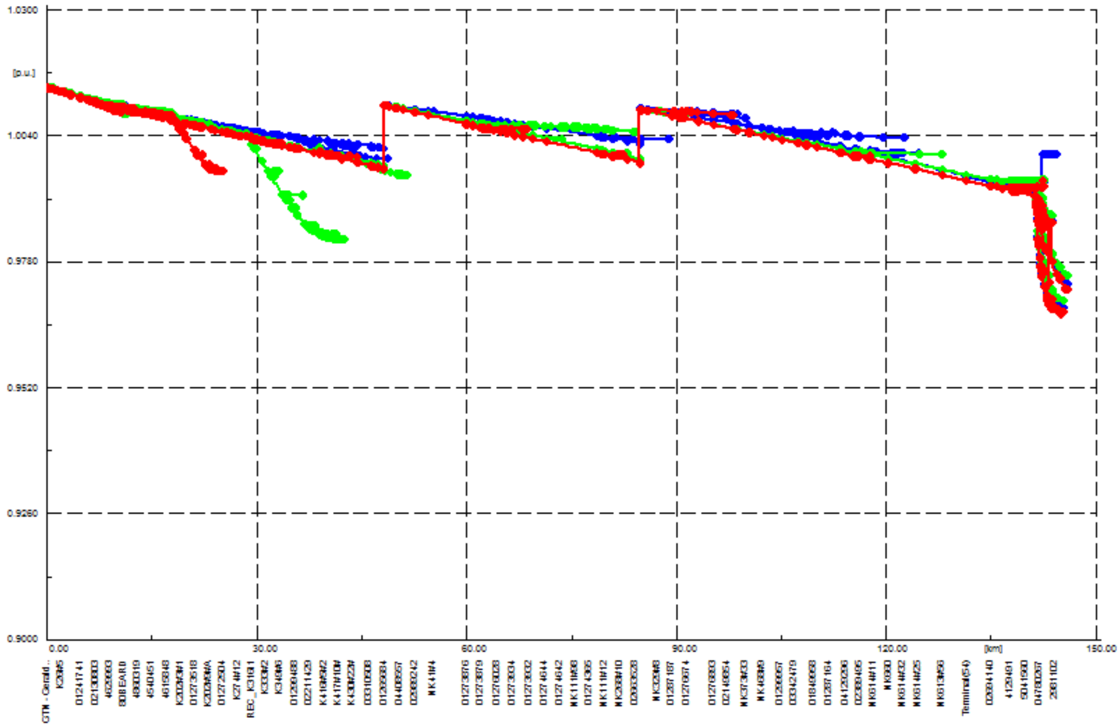


Figure 29. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Vf Control for Grid connected mode 100 % PV penetration with Overloaded battery at 138%

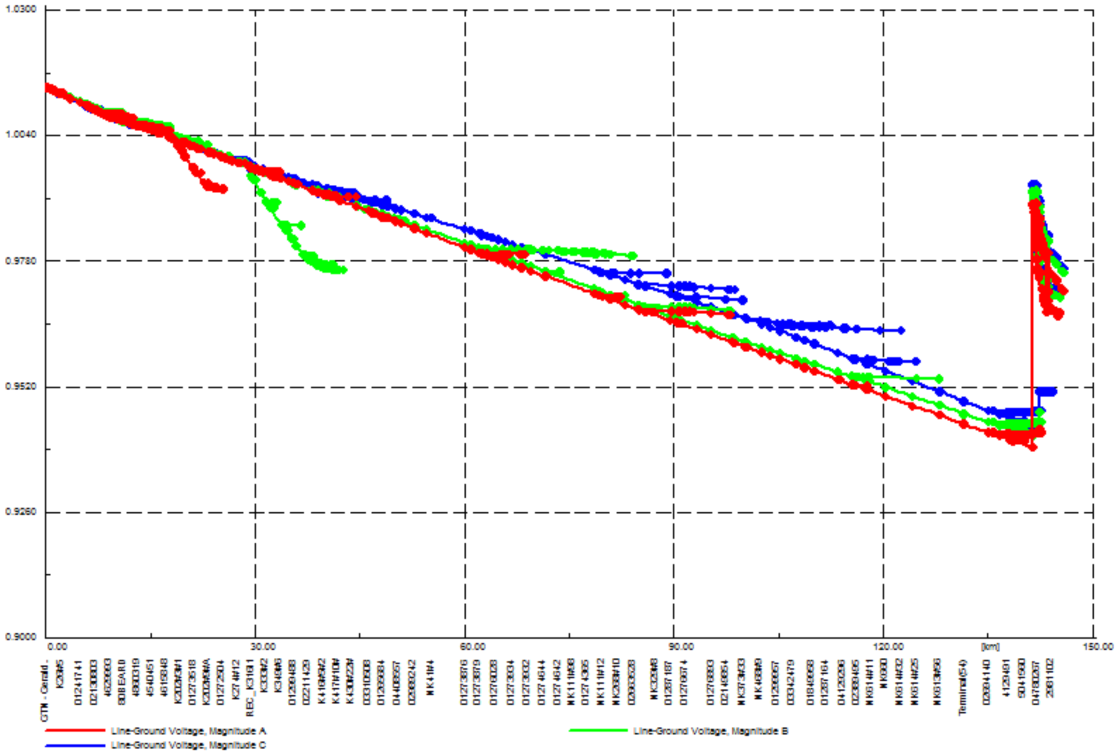


Figure 30. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Vf Control for Grid connected mode 50 % PV with No Voltage Regulators

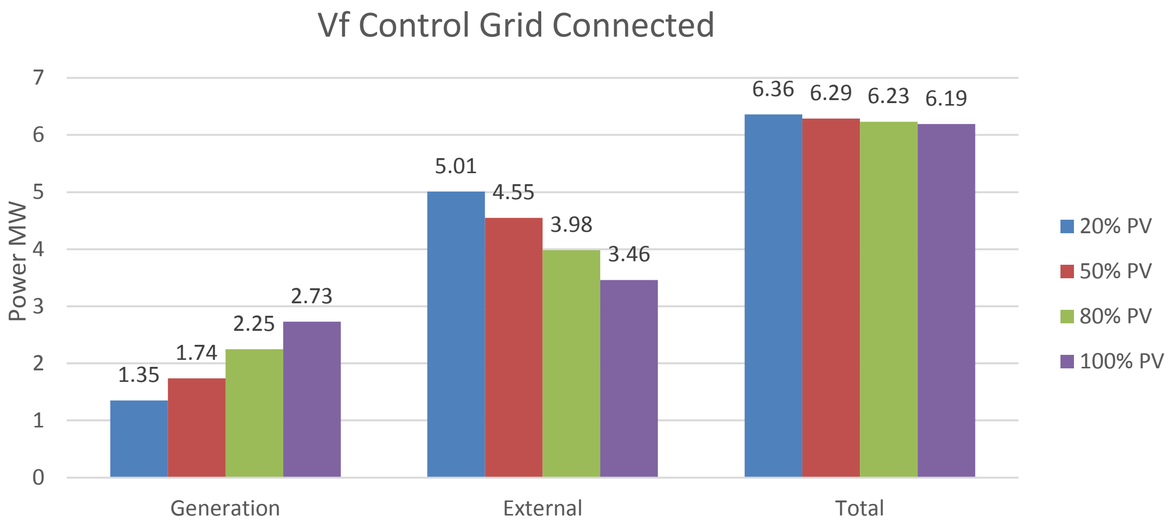


Figure 31. Power Comparisons for PV Penetration for Vf - Control

5.6.2 Discussion

The steady increase in PV penetration also increased the lowest voltage throughout the feeder, from 0.965 p.u. at 20%, 50% and 80%. As you can see, even though voltage quality drops a bit at the end of the feeder, overall the reliability is increased as the difference between voltages is decreased. Power Consumption was also reduced when local PV went from 20% to 80%, saving 120kW of power over the entire Kalbarri grid, but power was about 10kW more than other control simulations.

Also when micro grid is in grid connected mode with Vf control at 50 % PV penetration, with no Voltage Regulating transformers, it has the same overall voltage drop as the base case with the Voltage Regulating transformers, showing the great improvement in the grid caused by the PV generation at the load side.

5.7 Comparison of Results

	20% PV		50% PV		80% PV	
Control	low	high	low	high	low	high
PQ	0.9585	1.014	0.961	1.014	0.968	1.014
Droop	0.96	1.014	0.965	1.014	0.969	1.014
Vf	0.965	1.014	0.965	1.014	0.965	1.014

Table 1. Low and high voltage limits for PQ, Droop and Vf control over the Geraldton feeder at 20%, 50% and 80% PV penetration

Comparing the voltage limits shown in Table 1, it’s easier to see the difference in control and the effects it has on the main grid system.

Droop control has only slightly higher low voltage limit than the reference control, PQ. As explained in the Chapter 4, Droop control is commonly used to smooth out the reactions of two different types of control, rather than optimizing just efficiency or reliability. Coupled with the fact that the slaves are in PQ control, this strategy improves as power available increases.

Vf control is seen to have the highest low voltage at 20% PV and generally stays the same as the PV penetration increases, however in Chapter 5 the Voltage profiles for Vf control have less difference in the peaks and trough overall, staying close around 1 p.u at the cost of overdrawing power from the battery system, and requiring a little extra power.

5.8 Isolated Mode Results

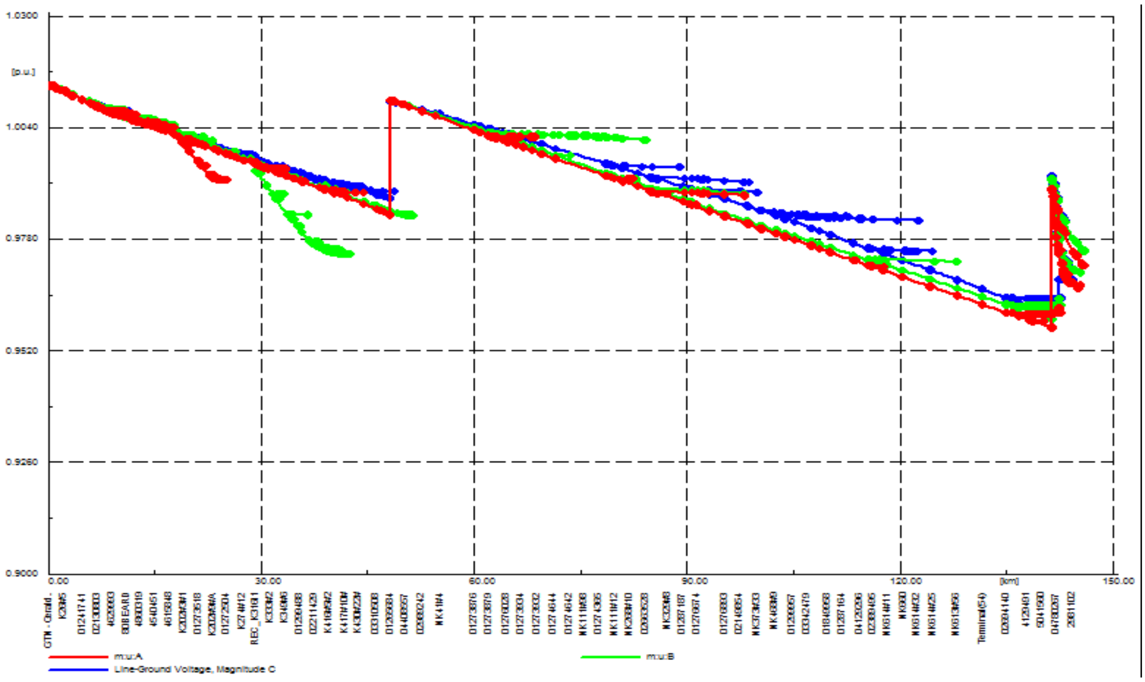


Figure 32. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Isolated mode with one Voltage Regulator

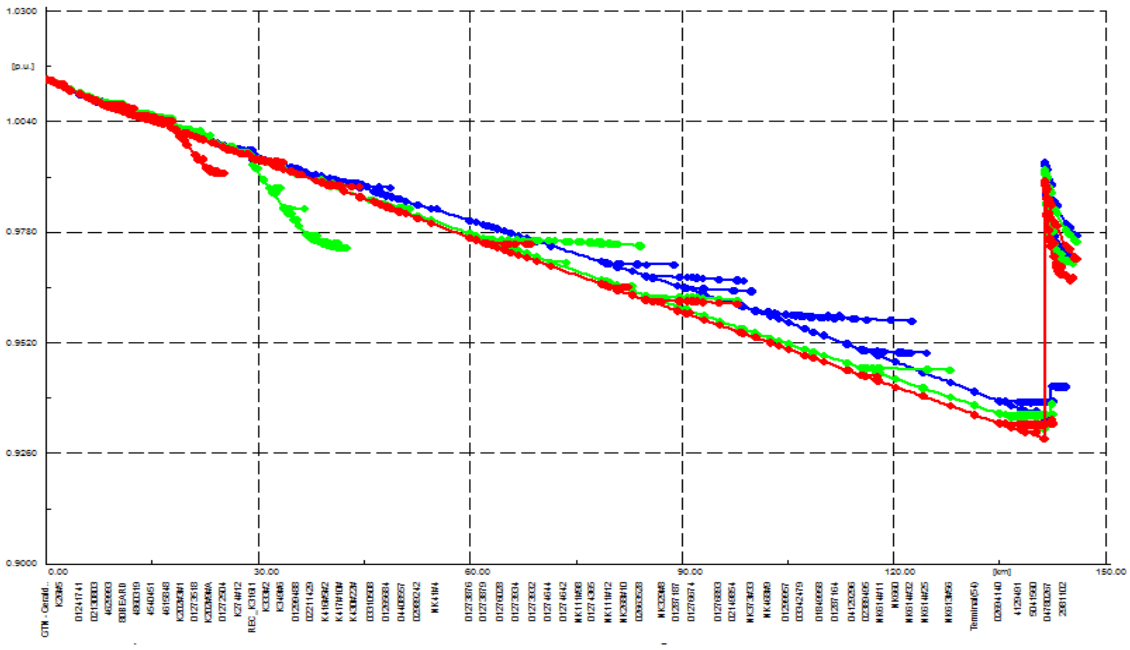


Figure 33. Voltage Profile of the extended feeder from the Geraldton Power Station showing the voltage p.u. as the feeder gets further away from the power station- Isolated mode with no Voltage Regulators

The above experiments demonstrated the isolated effects of the micro grid. In Figure 32, it shows the micro grid rendered one set of Voltage Regulators obsolete, by maintaining voltage above 0.95 along the feeder. And also presenting in Figure 33 above, in isolated mode, in comparing it to Figure 30 and how grid-connected mode provides better voltage standards in regards to main grid performance, due to the presence of control.

6 CONCLUSION

In Summary, the Integration of Micro grid technology into the Western Australian grid is a solution to infrastructural issues, reliability issues and peak demand that cripples our current grid so regularly.

As the case with Kalbarri showed, the end-of –line scenario doesn’t limit current standard micro grid control strategies. The integrated use of distributed sources increases efficiency as well as reliability and creates a sustainable network, without the need for patch up jobs like the Voltage regulating transformers on the Geraldton Feeder. The system is also flexible for extensions and has simplicity that allows it to work autonomously.

It improved the base case so voltage limits were met as well as decreasing power consumption to the entire Kalbarri grid by around 40kW in most cases

Droop control had some effect on the system reliability, but as described in Chapter 4 it tends to compromise between the Active Power/ Reactive Power and Voltage/ Frequency boundaries set, having almost the same results as PQ control.

Therefore I would recommend the Voltage controlled master and current controlled slaves as it has high voltage standard and consistency, with a little more power consumed, 10kW, due to its practicality as just the master control needs to change if needed. It was also exactly what this end of line feeder required as Droop control and PQ control were too passive in regards to improvement in reliability.

This confirms that certain scenarios require different approaches to control, so while certain strategies may work better for city embedded design, other control strategies need to be considered in end of line, industrial or isolated micro grid circumstances.

7 REFERENCES

[1] N. Hatziargyriou, “Microgrids : Architectures and Control,” Somerset, NJ, USA: John Wiley & Sons, Incorporated, 2013.

[2] M. N. S. Ariyasinghe and K. T. M. U. Hemapala, "Microgrid Test-Beds and Its Control Strategies," *Smart Grid and Renewable Energy,* vol. 4, pp. 11-17, Feb 2013.

[3] A. M. Bouzid, J. M. Guerrero, A. Cheriti, M. Bouhamida, P. Sicard, and M. Benghanem, "A survey on control of electric power distributed generation systems for microgrid applications," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 751-766, 4// 2015.

[4] A. L. Dimeas and N. D. Hatziargyriou, "Operation of Multiagent System for Microgrid Control," *IEEE TRANSACTIONS ON POWER SYSTEMS,* vol. 20, p. 9, 2005.

[5] Engineers Australia, "Infrastructure Report Card 2010 Western Australia," ed. Perth: Engineers Australia, 2010.

[6] M. Farina and G. Ferrari Trecate, "Decentralized and Distributed Control - Introduction," in *EECI-HYCON2 Graduate School on Control,* ed. Sup´elec, France, 2012.

[7] J. M. Guerrero, J. C. Vasquez, J. Matas, L. García de Vicuña, and M. Castilla, "Hierarchical control of Droop-Controlled AC and DC Microgrids - A General Approach towards Standardization," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,,* vol. 58, p. 15, 2011.

[8] W. Huang, M. Lua, and L. Zhang, "Survey on Microgrid Control Strategies," *Energy Procedia,* vol. 12, p. 7, 2011.

[9] A. V. Jayawardena, L. G. Meegahapola, S. Perera, and A. Robinson, "Dynamic Characteristics of a Hybrid Microgrid with Inverter and Non- Inverter Interfaced Renewable Energy Sources: A Case Study," presented at the Power System Technology (POWERCON), 2012 IEEE International Conference on, Auckland, 2012.

[10] B. Jones, N. Wilmot, A. Lark, d. d.-c.-w. s. l. 86.8px, t. 849.949px, f.-s. 30px, *et al.*, "Study on the impact of Photo-voltaic (PV) Generation on peak demand," ed. Perth: Western Power, 2012, p. 40.

[11] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews,* vol. 24, pp. 387-405, 8// 2013.

[12] A. Karabiber, C. Keles, A. Kaygusuz, and B. B. Alagoz, "An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids," *Renewable Energy,* vol. 52, pp. 251-259, 4// 2013.

[13] M. Khederzadeh, H. Maleki, and V. Asgharian, "Frequency control improvement of two adjacent microgrids in autonomous mode using back to back Voltage-Sourced Converters," *Electrical Power and Energy Systems,* pp. 126-133, 2015.

[14] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares*, et al.*, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *Power Systems, IEEE Transactions on,* vol. 19, pp. 1387-1401, 2004.

[15] F. Li, C. Shen, X. Wu, M. Zhao, and X. Huang, "A comparison of different control strategies in inverter connected micro-grids," in *Control Conference (CCC), 2014 33rd Chinese*, 2014, pp. 3563-3567.

[16] T. L. Logenthiran, R. T. Naayagi, W. L. Woo, V.-T. Phan, and K. Abidi, "Intelligent Control System for Microgrids Using Multi-Agent System," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. PP, p. 9, 2015.

[17] S. Love and M. Nahan, "WESTERN POWER - POWER OUTAGES - KALBARRI
Grievances," in *ASSEMBLY — Thursday, 3 April 2014*, Parliament of Australia, 2014.

[18] M. Majwi, "Micro-grids with Distributed Generators in an Edge-of-Main Grid Scenario," Bachelor of Electrical Engineering, Engineering and Computing, Murdoch University, Perth, 2009.

[19] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani*, et al.*, "Trends in Microgrid Control," *IEEE TRANSACTIONS ON SMART GRID,* vol. 5, p. 15, 2014.

[20] O. Palizban and K. Kauhaniemi, "Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 797-813, 4// 2015.

[21] E. Planas, J. Andreu, J. I. Gárate, I. Martínez de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renewable and Sustainable Energy Reviews,* vol. 43, pp. 726-749, 3// 2015.

[22] Western Power, "Western Power annual Planning Report 2014/15," ed, 2014, p. 140.

[23] Western Power, "Western Power Annual Report 2014," ed, 2014, p. 120.

[24] Western Power, "Western Power Electricity Market Review
Submission

October 2014," ed, 2014, p. 16.

[25] Western Power, “Study on the impact of photovoltaic generation on peak demand”, ed, 2012, p. 40

[26] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodr´ıguez, "Control of Power Converters in AC Microgrids," *IEEE TRANSACTIONS ON POWER ELECTRONICS,* vol. 27, p. 16, 2012.

[27] J. L. Rueda and F. M. Gonzalez-Longatt, *PowerFactory Applications for Power System Analysis*. Cham: Springer, 2014.

[28] A. A. Salam, A. Mohamed, and M. A. Hannan, "Technical Challenges on Microgrids," *ARPN Journal of Engineering and Applied Sciences,* vol. 3, p. 6, 2008.

[29] N. L. Soultanis, S. A. Papathanasiou, and N. D. Hatziargyriou, "A Stability Algorithm for the Dynamic Analysis of Inverter Dominated Unbalanced LV Microgrids," *Power Systems, IEEE Transactions on,* vol. 22, pp. 294-304, 2007.

[30] A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification," *Proceedings of the IEEE,* vol. 99, pp. 119-132, 2011.

[31] V. Verma and G. G. Talpur, "Decentralized Master-Slave operation of microgrid using current controlled distributed generation sources," in *Power Electronics, Drives and Energy Systems (PEDES), 2012 IEEE International Conference on*, 2012, pp. 1-6.

[32] X. Xiaoyan, Y. Huang, G. He, H. Zhao, and W. Wang, "Modeling of large grid-integrated PV station and analysis its impact on grid voltage," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on,* 2009, pp. 1-6.

[33] F. Xie. (2014). *Evaluation of voltage control methods for maximizing end-of-grid wind farm capacity using the Kalbarri Wind Farm as a study case*. Available: http://researchrepository.murdoch.edu.au/25668/

8 APPENDICES