THE SAFETY RISK ASSESSMENT AND MITIGATION MEASURES OF THE LV NETWORKS WITH EMBEDDED GENERATORS

By

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Abbreviations

- ADD – After Diversity Demand
- CFL – Compact Fluorescent Lamp
- DB – Distribution Board
- DS – Distribution System
- EG – Embedded Generation
- ENS – External Network Device
- EDS – External Disconnecting Switch
- GC – Grid Code
- IEA – International Energy Agency
- LV – Low Voltage
- MV – Medium Voltage
- MSD – Mains Monitoring Units
- MCB – Main Circuit Breaker
- NDZ – Non Detection Zone
- NERSA – National Electricity Regulator of South Africa
- NRS – National Requirements Specification
- O&M – Operations and Maintenance
- OVP – Over Voltage Protection
- OFP – Over Frequency Protection
- PCC – Point of Common Coupling
- PLL – Phase Locked Loop
- PV – Photovoltaic
- PWM – Pulse Width Modulation
- SFS – Sandia Frequency Shift
- TS – Transmission System
- UFP – Under Frequency Protection
- U/OVP – Under / Overvoltage Protection
- U/OFP – Under / Over frequency Protection
- US – United State
- UVP – Under Voltage Protection

Abstract

Electricity industry liberalization across the world has seen a significant growth in the utilization of autonomous- and distributed power sources deployed at sub-transmission (132 - 33 kV) and reticulation levels (<33kV) in stand-alone or grid connection notations. With the electricity industry reform, an open access regime is a standard policy governing the transmission grid, and this provides for full competition at generation and distribution end of the delivery value chain. The National Electricity Regulator of South Africa (NERSA) is currently examining a roll out plan for a nation-wide rooftop photovoltaic (PV) system. Most of these roof top PV systems are expected to be connected on the low voltage (LV) networks (<1kV). The widespread deployment of such PV installations have associated risks to personnel and could pose challenges to system operations. Most utility field service engineers are not aware of the dangers posed by such installations. Dangers may include but are not limited to reverse power flow from installed PV systems should the anti-islanding protection fail after the loss of utility supply. This research investigation presents results from the analyses of the impact of statutory requirement, load demand and load type on the embedded generator (EG) grid–tied inverter anti-islanding protection settings and anti-islanding non-detection zone to minimize or reduce LV network operating safety risk upon the loss of utility supply.

Chapter 1: Introduction

1.1 Background

Eskom is experiencing a rapid growth in Embedded Generation (EG) such as photovoltaic (PV) systems. The Embedded Generation growth is expected to change the normal load flow through the Eskom Networks. Currently, power flows in distribution medium voltage (MV) and low voltage (LV) Networks is unidirectional, it flows from the point of connection with the Sub-Transmission Network down to MV and LV Customers. With the introduction of Embedded Generation, power flows may reverse direction especially when the wind or solar generation is high. Distribution Networks may even becoming net exporters of power. Thus, this situation may create many technical problems with respect to network operating and maintenance, network protection settings, voltage regulation, load modelling, system security, system performance, load shedding and so on.

Regarding network operating and maintenance, it is anticipated that it will be difficult to isolate the network under certain loading condition due to the type and design characteristics of Embedded Generators. One of the main requirements for Embedded Generator is an anti-islanding functionality [1]. This means that when the grid supply (Eskom) is lost, the Embedded Generator is expected to disconnect itself from the network via anti-islanding mechanism. But under certain loading conditions, this functionality may fail causing a Network Island in which the Embedded Generators will continue to power an islanded network even though the utility source power is no longer available. Islanded network can be unsafe to utility (Eskom) field staff, who may not realise that the network is still energised. Therefore, operational safety risks and benefits of various anti-islanding methods need to be studied, evaluated and improved where necessary.

Furthermore, Eskom does not have safe work practices in place for the LV Networks with Embedded Generators. Currently, Eskom LV operating philosophy requires the operator to Identify, Open, Isolate, Tag and Lock out, and Test the circuit before performing any work [2]. This operating procedure is adequate for LV Networks without EGs. The challenge is on the LV Networks with EGs, since power flow is no longer unidirectional and it is extremely difficult for the operators to perform any maintenance task more especially on feeders with multiple sources / Embedded Generators from various geographic locations.

In addition, the point of isolation on the network is currently mapped, reflected in operating diagrams, factored into the operating regime and singular in most cases. Embedded Generation has introduced multiple injection points which may be difficult to identify on multiple feeders. This puts Eskom staff and contractors at safety risk. Hence, a new operating philosophy is required to cater for new challenges created by introduction of Embedded Generation.

1.2 Objectives

The main objective of the study is to:

- Eliminate or mitigate any hazard or potential hazard to safety or health of employees due to introduction of Embedded Generation.
- Optimise Eskom network performance with respect to voltage stability, power flow and frequency stability. Also taking into account load shedding requirement.
- Evaluate Operating patterns on rural schemes and establish Embedded Generation recovery time suitable for rural conditions. (Note: recovery time after utility supply restoration in order to allow for Utility supply stability during network fault finding incidents).
- Evaluate the risk and benefit associated with various Islanding Detection Methods with respect to Eskom operational requirement. The Islanding Detection Methods to be analysed include the following:
    - Passive Methods such as Under/Over Voltage, Under/Over Frequency, and Voltage Phase Jump detection
    - Active Methods such as Impedance Measurements and Frequency Bias
- Finally the study recommends risk optimisation and or mitigation measures based on robust and reliable technologies and procedures.

1.3 Thesis Structure

Chapter Two covers literature review with respect to the current operating practices and challenges that other countries are facing due to Embedded Generation.

In Chapter Three, Eskom’s current network design and operating philosophy is discussed in detailed. There are two aspects discussed, namely: LV Network without EG and LV Networks with EG.

Chapter Four discusses the statutory requirements that have been put in place to address the minimum mandatory requirement for EG connections to the LV networks. These statutory requirements aims at minimising design and operational challenges around the sizing of units in (kW), operating voltage limits, operating frequency limits, power factor and anti-islanding requirements for better network performance and security of supply.

Chapter Five presents various methods in which anti-islanding can be achieved in order to isolate all EGs during loss of utility supply.

In Chapter Six, anti-islanding failure modes are discussed. Pros and cons of each anti-islanding method under various network operational conditions are discussed.

In Chapter Seven presents the case study in which all anti-islanding types are evaluated with respect to one another when connected to the network.

Lastly, the conclusion and recommendations of this thesis work are presented in Chapter Eight

Chapter 2: Literature Review on LV Networks with EGs

Recent pressures due to environmental requirement to reduce levels of CO_2 emissions and the increase of electricity tariffs have led to active efforts toward deploying renewable smaller-scale power generation to the end users. This is referred to as Embedded Generation (EG).

Generally, the primary energy for Embedded Generation is renewable resources such as hydro, wind, biomass and solar. The primary energy source to a large degree dictates the energy collector part (e.g. PV, wind turbine, etc.) of an Embedded Generator while the grid connection is mostly via a DC to AC inverter which is dependent on the grid voltage as a reference. Most of the network interconnection requirements are performed and achieved via the inverter. Therefore the EG and inverter are used interchangeable.

Renewable energy generation is greatly encouraged through various government policies. However, due to the historical low voltage (LV) distribution network topology in South Africa that is radial rather than meshed, there are technical bottle necks and legislation hindering the connection of grid-tied EG. Traditionally in the LV network, power and short-circuit currents flow in one direction from MV/LV transformer to the customers hence LV protection and metering devices are designed based on this configuration. Since, the connection of EG introduces new challenges such as reverse power flow on the LV Network. Therefore, this requires revision of LV Design, Operating and Maintenance Philosophies to cater for reverse power flow and to ensure safety of public, staff and equipment.

The electricity industry in South Africa is currently addressing the issues of interconnecting EG to the utility LV network [1]. There are standards and regulations that have been put in place to deal with Network Performance issues but little has been done to address human safety, hence this study. Although across many developed countries EG are no longer a new technology, a lot of work has been done by them to minimise the safety risk. However, South Africa cannot adopt most of the philosophies and guidelines that has been established for developed countries. This is due to unique challenges that South Africa has such as LV network design limitations (i.e. portable earthing is not provided for in current LV networks for employee safety when work is in progress); LV Network are not remotely visible; long hours of load shedding / outages amongst other issues, which are not widely experienced in developed countries. Therefore, the EG is treated as new technology as it brings new experience for the electrical industry in South Africa. Nevertheless, there has been some progress in development of standards and guidelines to reduce the impact on the current operating model taking into account all challenges highlighted above.

The electrical industry in South Africa has developed standards that specifies minimum technical requirement for the design, installation, maintenance and operations of Embedded Generators. This is to ensure that general public, network operators, and customers are safe. The EG design and installation is guided by:

- Grid Connection Code for Renewable power Plants (RPPs) Connected to Electricity Transmission System (TS) or The Distribution System (DS) in South Africa [1]
- National Requirements Specification (NRS), Grid Interconnection of Embedded Generation, part 2: Small Scale Imbedded Generation [3]

Grid Connection Code for Renewable power Plants (RPPs) Connected to Electricity Transmission System (TS) or The Distribution System (DS) in South Africa [1] controls the connection of Embedded Generators to the utility network by limiting generating capacity. The Grid Interconnection of Embedded Generation, part 2: Small Scale Imbedded Generation (NRS-097-2-1) [3] documents specify designs and performance requirements such as anti-islanding protection functionality on the Embedded Generation to protect against a Network Island.

A Network Island occurs when the utility supply is disconnected and the Embedded Generators in the disconnected network continue to supply loads [4]. The Network Island may occur due to various reasons such as intentional switching and faults on the network [5] which results in isolating other parts of the network. As a minimum requirement to prevent a Network Island, grid-tied inverters should have an under/over frequency protection methods (U/OFP) and under/over voltage protection methods (U/OVP) to stop the generation if the voltage magnitude and or the frequency drifts outside the normal operating range [6] as a result of the utility supply disconnection.

If a Network Island is not protected against, the utility personnel working on the network which is assumed to be de-energised is at risk of electrocution. Also a Network Island may damage customer equipment since the quality of supply is no longer regulated. If the utility network supply is restored, the islanded network may be out of synchronism with the grid which could cause damage on the utility and customer equipment due to inrush currents and over-voltages. Therefore, the system should be designed, installed and operated such that a Network Island does not occur [4].

Studies are required to evaluate risk levels of Islanding for EG installations and specify risk control measures to minimise impact of the identified risks. Risk of islanding is mainly dependent on the type of customer load, size of customer load with respect to the EG supply, number and type of EGs in parallel. For a Network Island to occur the supply and demand must be balanced. Therefore, constant power load type will have low risk of islanding as it is highly unlikely to balance supply and demand in the network. However, other load types (i.e. voltage and frequency dependant loads) are high risk because they do not need to be 100% matched for a Network Island to occur. A small mismatch within 30% is adequate to cause an island.

One way to avoid Network Island from occurring is to ensure that the EG generation and load demand mismatch is high enough (i.e. above 30%) to push the system out of bound (i.e. out of normal operating range) during loss of utility supply. This may be achieved through various methods that are employed by EG to detect loss of Utility supply such as active protection scheme that injects disturbance signal to the system. The aim of such schemes is to push the network out of bound (i.e. outside the normal operating limits) by creating power mismatch when the utility supply is disconnected [7]. However, this protection method may still fail if the injected disturbance signal coincidently balances out power mismatch which already exist [7].

In addition, if there are various EGs connected in parallel the risk of anti-Islanding is high also. The active protection scheme may work for a single connected EG, but may not work for multiple parallel connected EGs in the operating zone. With multiple EGs, the injected disturbance signals from different EGs may cancel one another if not synchronised which may result in non-detection of an island. This is referred to as inverter (EG) dilution effect. Therefore, active protection schemes always have challenges when there are various EGs connected in parallel in a network [7], [5].

Studies have been performed to evaluate anti-islanding on paralleled inverters (EGs) on both the U.S. and the German inverters. When the paralleled solar PV inverters (EGs) were isolated with various amounts of load (including closely matching the load to generation) for multiple tests, the results suggested that these aggregated devices cannot sustain an islanded condition [8]. However, according to another study done on Sandia Frequency Shift (SFS) anti-islanding method to the presence of inverters without SFS system can cause all the inverters located in the same network to fail faced with an islanding situation [6]. Moreover, the presence of generators with different trigger delays could increase the probability of islanding.

2.1 Personnel Safety

It is required that the EG installation shall not endanger utility personnel working on the network during outages; utility customers and the public at large [1]. Since, EG is a new technology that introduces various electrical energy sources in the LV network which historically had a single source of supply. Operating standards and procedures for LV network with a single source of supply (i.e. utility supply only) are presently available and adequate to address all safety related matters with respect to network operations and maintenance. Now that the LV network is evolving it then requires an improvement on the existing LV network operating standards and procedures to cater for networks with multiple energy sources, Embedded Generation.

In the event of an outage on the LV network with Embedded Generators, a network operator will be endangered from an EG if the following actions occur [9]:

- The EG fails to detect loss of utility supply
- The utility personnel fail to test for dead voltage before executing any work.

Therefore, the utility staff will only be at risk from the EG if the both above events occur.

It is dangerous to rely on anti-islanding protection alone since it may fail. The U/OVP and U/OFP method is required for every inverter / EG but has high risk of Non-detection Zone (NDZ) [4]. None detection zone NDZ occurs when both active and reactive power generated by the EG is closely matched with the load demand within an operating zone or island such that when the grid is disconnected there is a small change in system parameters such as voltage and frequency and not detected by islanding method [5]. As a result, some utilities requires customers to install external disconnect switch (EDS) that is accessible to the utility staff for manual operation as an extra protection should islanding occur [9]. It allows the EG to be disconnected manually instead of relying on automatic anti-islanding switch. In the US, it has been an issue of debate between public and utilities whether this switch is required or not [9]. The same debate has started in the South Africa too. There are suggestions that it is not practical to use EDS because it may delay network operations and customer restoration after an outage if the network operators are required to manually switch the individual residential customers on and off. This is based on the fact that utilities are required to reduce outage duration and they are penalised if they do not meet the performance targets set by their regulators [9]. As a result the network operators get penalised through incentive scheme if the network is not restored within specified performance targets. Since safety and restoring power are both priorities of the utility but the presence of external disconnect switch (EDS) tends to increase customer restoration time. Hence, the use of EDS may be ineffective especially when there is a large system outage. Therefore, utilities should always strike a balance between technical performance, safety and economical requirement to fulfil their obligation to work in an economical, reliable and safe manner [9].

In some applications, external devices are used for detecting islanding. This may be expensive for micro Embedded Generators. Also if the islanding protection scheme uses the same active anti-islanding methods discussed above, it may still present the same problems as Embedded Generators connected in parallel [7].

To prevent Network Islanding and to ensure safety of staff some studies propose the use of transfer trip. A transfer trip is when the utility circuit breaker status is communicated with the corresponding EG customer circuit breaker to isolate Embedded Generation when required to do so [7]. Unlike the manual EDS, this will ensure a faster customer restoration period. Although, the transfer trip is a better solution but it can be expensive for smaller EGs. Also, most distribution networks in the developed countries are designed to provide multiple alternative source of supply (i.e. back-feeding capabilities) to a particular feeder section / customers. This is referred to as meshed network. In meshed networks transfer trips can be complex to implement. It may require trip signals from several network points to be communicated and coordinated even during back feed configuration. This will require network configuration status to be updated and communicated accordingly to the relevant EGs at any given configuration in time [7]. However, this does not present a big issue in South Africa since LV networks are radial (i.e. there is only one network configuration status always) and networks are not designed to back feed. The transfer trip can be implemented much easily on such (radial) networks and could speed up customer restoration time and improve staff safety.

2.2 Network Performance

2.2.1 Power Quality

Connection and operation of the Embedded Generators shall not degrade the network reliability and quality of supply during all operating conditions [4]. However, Power-Quality degradation is anticipated due to active anti-islanding method which allows EG to inject disturbance signals into the network in order to drive the voltage and frequency away from normal operating point. Network degradation will increase as the number of EGs (i.e. active methods of various types) increases on the network. Large number of Embedded Generators or high EG penetration levels will result in a noticeable degradation of power quality even at normal system operating condition (i.e. system healthy condition) [7].

2.2.2 Voltage Regulation

The integration of EG to the utility network can have negative impact on voltage regulation. It is important to maintain voltages on the network within an acceptable operating range under all operating conditions to avoid damage on electrical equipment. The impact of extremely low or high voltages on electrical equipment can be detrimental for example continuous high voltages can lead to breakdown of insulation and low voltages can lead to malfunctioning of electronic equipment. This require consideration for integration of EG to the LV network to ensure safety of public, staff and equipment. Most customer appliances are not protected against high and low system voltages; therefore it is the responsibility of the utility to ensure that voltages are within normal operating limits.

The introduction of EG to the LV networks increases the generation of active power mostly which result in voltage rise along the feeder. The voltage increase along the LV feeder may exceed the normal operating limits stipulated in the South African Grid Code and or may cause unexpected tripping of EGs on the network [10]. This may cause voltage instability or fluctuation because the tripped EGs may reconnect again and a similar incident may repeat.

To control voltage fluctuations on the system due to EG connection, some international Electricity Regulators like German GC [6] requires the maximum voltage variation at the point of common coupling (PCC) after the connection of a EG to be 3% and the PV capacity to be limited based on equation 1 below [10]:

$$\boldsymbol{V_{pcc} \leq 1.03V_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (1)$$

Where: V_n is the voltage at the PCC before the connection of the PV system

Therefore, in order to comply with this requirement, a lot of network reinforcement is required upfront before any EG connection is implemented to prevent equipment failure and improve human safety. Thus, it is not ideal for South African LV network, better voltage regulation strategies with minimal investment cost are be investigated further.

2.3 Chapter in perspective

Most countries have adopted various strategies for Embedded Generation integration. For instance, in the Netherlands they require anti-islanding schemes that are based on frequency changes whereas other countries like Germany and Austria require methods that are based on sudden impedance changes. United States requires inverters for grid connection that are certified for that purpose. Each country has unique requirement hence unique Embedded Generation integration strategy.

It should be noted that South Africa has a unique network topology, network performance requirement, and cultural behaviour. Therefore it is critical for South Africa (Eskom) to adopt a strategy that is suitable for its operating environment to ensure safety of plant, staff and public under all operating conditions.

Chapter 3: Current Network Design and Operating Philosophies

3.1 LV Networks Without EG

Currently in Eskom, power flows in distribution LV networks is unidirectional, it flows from the point of connection with the sub-transmission and MV network down to LV customers and there is no generation required on the LV network. The only form of generation that is allowed is a standby generation that is when a customer is completely isolated from the utility network [12]

There are three possible operating zones in the LV network, namely:

- The MV/LV transformer zone is where the LV networks starts, just after MV/LV transformer. It then supplies several pole top box or stuby that feeds to LV customer via service cable.
- Pole top box or stuby zone is where customer service cable is connected to. Normally each customer or a group of four customers are connected through a circuit breaker.
- Customer zone is an individual customer zone (service cable)

This is depicted in Figure 1

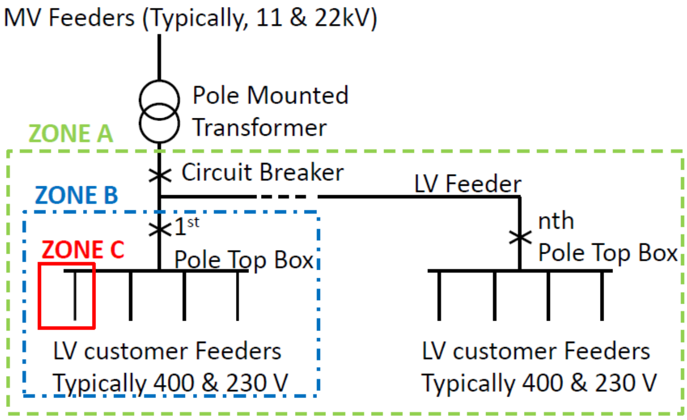

Figure 1: Network Operating Zones

When performing maintenance on each of the zones, the current operating philosophy requires the operator to perform the following safety procedure before execution of work [2]:

- Identify the circuit
- Open and Isolate the circuit (i.e. remove all source of electrical energy)

- Tag and Lock out the circuit
- Test for dead
- Execute the work

Since LV customers are not allowed to generate to the Grid and the power flow is unidirectional, from the utility to the customer. It is therefore easy for the network operator to perform the above safety procedure since there is only one source of electrical energy that is the utility supply. Once the circuit has been identified, opened, isolated, tagged and locked out from the utility side, it is almost guaranteed to be dead and therefore safe to perform work. There are systems and databases in place that are used to manage this safety procedure.

If the network is isolated upstream, it is deemed to be safe to perform work on any part of the network downstream after the isolation point. The LV network has been successfully managed in this manner in past without incidents when procedure are followed properly. A typical MV rural feeder is shown in Figure 2 highlighted in red. Assuming it supplies LV customers without EGs via a 16kVA transformer, for example. When this network is isolated at the MV/LV transformer for maintenance activity on any of the zones (i.e. the transformer and the pole top box zones are highlighted in blue and yellow, respectively), the network downstream is guaranteed to be dead since there is only source of energy and work can be performed safely.

Figure 2: Typical LV Rural Feeder – Showing Operating Zones

The introduction of EG on the LV network will change that network behaviour, details are discussed in the next section.

3.2 LV Networks With EG

The introduction of EG on the LV network is bound to introduce fundamental changes to the current Network Operating and Control practices in Eskom that have limited organisation support capacity. Power flows in the LV networks may no longer be unidirectional, that is from the point of connection with the utility network down to customers. In many cases the power flows may reverse direction especially when the wind or solar power generation is high, with LV customers becoming net exporters of power. That situation may create many technical problems with respect to network operating. The normal operating safety procedure, presented in section 3.1, may no longer be applicable. Current Operating Procedure will require modification or the LV network will require design upgrade to cater for multiple electrical sources. The network will no longer be isolated from the utility side only; it will require a process to isolate from the customer side as well. Over and above the circuit isolation the EG will have impact on other operational performance related issues such as auto-reclose, power quality, network protection settings, voltage drops, load shedding schemes, etc. which require attention as well.

3.2.1 Impact of EG on Auto-reclose

Although EG are mandatory to have an anti-islanding protection scheme to ensure that once the utility supply is off the customer supply stays off until utility supply is restored. Such protection schemes are prone to failure under certain network configuration, loading and generation conditions. There are several concerns associated with anti-islanding failure, these include but not limited to [13]:

- Out of phase reclosing - may result in damaging the EG equipment, or other customers equipment
- Power Quality – since the utility is responsible for power quality, it may fail to control voltage and frequency in an islanded network which may damage the customer's equipment as a results of frequency and or voltage deviation outside of the acceptable operational ranges
- Safety Hazard – The network may remain energised that is assumed to be dead.

Some distribution networks have auto-reclosers installed to reduce the impact of transient faults and to improve availability of power supply to the customers. The auto-reclose protection function automatically closes the breaker within one second (typically) after it has tripped due to the network fault. For transient faults the network is expected to stabilise after auto-reclose protection action. Transient faults remove themselves from the network either by its own momentum, gravity or burning clear as a result of the fault current rapidly allowing the network to restore itself after the first of successive breaker reclose. However, for permanent faults (i.e. permanent insulation failure), the auto-reclose protection action will repeat few times until till the breaker locks out and the faulted network will be disconnected.

At the same time the EG is expected to disconnect during loss of utility supply. However, the EG interconnection specification recommends a disconnecting or tripping time of two seconds after the loss of utility supply. Thus, during transient faults, it is likely to close the utility supply breaker while the EG is still connected which could result in out of phase reclose. If such condition prevails the voltage across the utility breaker may be doubled as a worst case scenario. This condition is explained in detailed in Figure 3 and equation 2.

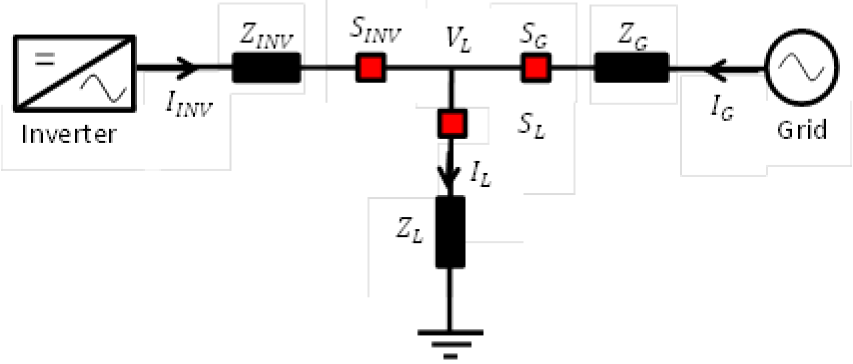

Figure 3: Auto-reclose on Networks with EG's

$$V_L = \sqrt{V_G^2 + \mathrm{V}_{INV}^2 - 2\mathrm{V}_{INV} S_G cos(\delta)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (2)$$

Where:

- δ is the angle between the grid voltage and the EG / islanded network voltage
- V_G is the utility voltage
- V_{INV} is the inverter voltage

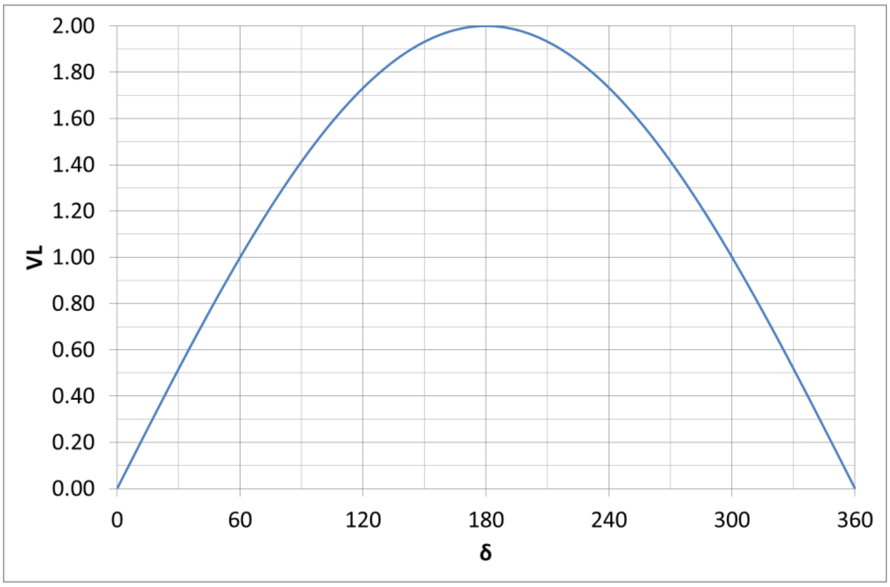

Figure 4: Voltage across the utility breaker during auto-reclose [13]

Worst case is when the angle is 180 degrees between the two sources.

When the utility supply is disconnected from the EG inverter, the inverter does not disconnect instantaneously. There is a time delay before it shuts down. This time delay depends on several issues such as load, anti-islanding detection method, etc. The auto-recloser settings should cater for worst-case shutdown time delay in a zone to avoid over-voltages due to out of phase reclosing in the network. This has a negative impact on power quality and public safety.

3.3 Chapter in perspective

Eskom LV network design should cater for EG for safety operating and maintenance of the network. This will also require the existing operating procedures to be revised in order to address problems associated with reverse power that is introduced by EG. It is recommended to install smart grid technology in order to improve network visibility and operability. This will also enhance fault finding and improve identification of EG on the network.

Chapter 4: EG Interconnection Requirements

The South African Renewable Grid Code and the National Requirement Specification (NRS) documents have been established to standardise the minimum technical requirements for interconnection of Embedded Generation (i.e. renewable energy) to Transmission System (TS) or Distribution System (DS) [1], [3]. These are compulsory requirements for all EG types.

Renewable power producers, required to connect to LV network are sub-divided into three categories based on their existing power usage. There are small, medium and large power users shown as A1, A2 and A3 in Table 1, respectively. Each customer category has a specific connection requirement with respect to maximum power output, operating voltage range and frequency. This thesis evaluates the impact of these requirements in terms of human safety as well as estimates the anti-islanding performance of embedded generation per customer category.

The Grid code requirement is extended further in the National Requirements Specification 097-2-1 (NRS) as shown in Table 2. According to the NRS 097-2-1 requirement, the maximum generation that can be connected on the LV network (residential) is 13.8. kVA (all LV generators are assumed to operate at unity power factor). The limiting factor is the Notified Maximum Demand (NMD) or service circuit breaker size.

Table 1: Grid Code Requirement [1].

Category	**A1**	**A2**	**A3**
Power Output (kVA)	0 to 13.8	13.8 to 100	100 to 1000
Voltage Level (V)	0 to 1000		
Operating Frequency	49 to 51		
Operating Voltage Range	-15 to + 10%		
Operating Power Range	20 to 100%		
Low Voltage Ride through	60% for 0.15 s		
Power Factor	0.95		

Table 2: NRS 097-2-1 Requirement [3]

Number of Phases	Service Circuit Breaker Size (A)	NMD	Generation Limit (kVA)
1	20	4.6	1.2
1	60	13.8	3.45
1	80	18.4	4.6
3	60 and 80	41.4	13.8

Most of these parameters were selected to minimise the impact in terms of EG penetration levels and to minimise the impact on voltage regulation and network thermal limitation.

4.1 Anti-Islanding Requirement

The anti-islanding requirement is stipulated in the NRS-097-02-1 [3], which requires an Embedded Generator (EG) to use an active islanding detection method that will ensure that the EG ceases to energize the utility network within 2s of an unintentional islanding forming if operating voltage drops or rise below or above normal operating threshold. Table 3 shows voltage rage and maximum trip time that is require for Anti-Islanding of EG.

Table 3: Anti-Islanding Requirement [3]

Voltage Range	Maximum Trip time
V , 50%	0.2 Sec
50 % ≤ V < 85 %	2 Sec
85 % ≤ V ≤ 110 %	Continuous operation
110 % < V < 120 %	2 Sec
120 % ≤ V	0,16 Sec

4.2 Chapter in perspective

The South African Grid Code for Renewable is too generic in terms of the EG capacity that could be installed on the LV network (residential). It doesn’t take into account the current network design limitations. For example, it allows up to 1MW which is too large (in EG size) for LV network and may be challenging to operate. However The National Requirements

Specification (NRS) does improve the LV Embedded Generation specification. The requirement specified in the NRS097-2-1 [3] document is more practical to implement.

Chapter 5: Anti-Islanding Methods

The primary energy for Embedded Generation is renewable resources. This includes Hydro, Wind, Biomass and Solar as depicted in block diagram in Figure 5. The primary energy source to a large degree dictates the energy collector part (e.g. PV, wind turbine, etc.) of an Embedded Generator while the grid connection is always via a DC to AC inverter which is dependent on the grid voltage as a reference.

Some of the grid interconnection requirements such as anti-islanding are performed via the inverter. This chapter will discuss anti-islanding methods within an inverter and assuming that the energy collector is photovoltaic (PV).

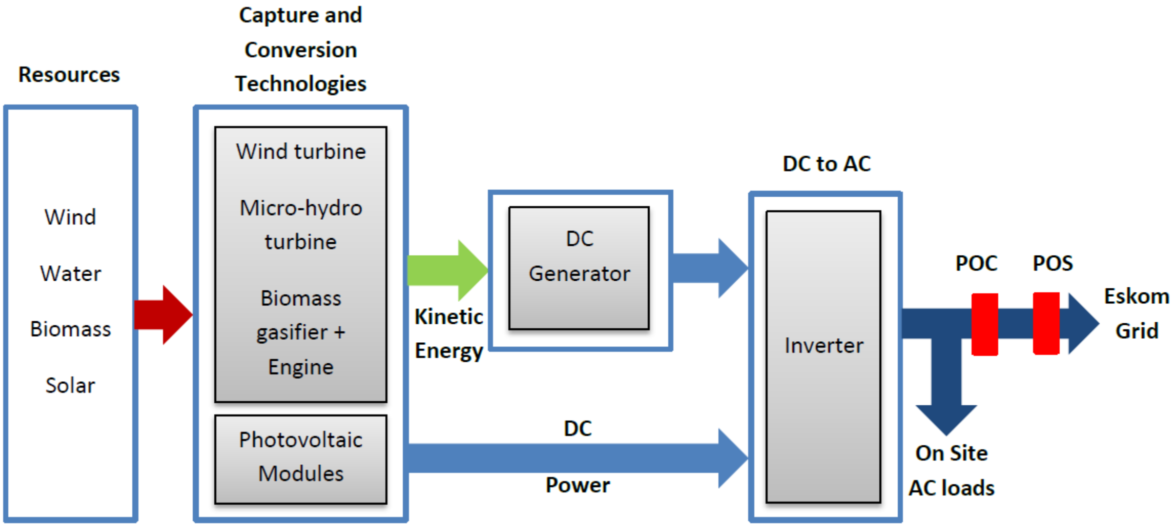

Figure 5: General Layout of Renewable Energy

Different anti-islanding methods have been established [14]. The anti-islanding methods are categorised into two classes, namely:

- Local anti-islanding detection methods
- Remote anti-islanding detection methods

Local islanding detection methods reside in the inverter and are based measurements of the system parameters such as voltage and frequency at the terminals of the EG while remote islanding detection method is based on the communication between the utility grid and the EG regarding the network status and configuration.

This thesis concentrates on the local anti-islanding detection method. Local detection method is grouped into two categories which are passive and active methods. The grid tied inverter (i.e. EG) may either use any of the two methods.

In the active method the inverter injects a disturbance signal which could be current or harmonics at a defined rate and magnitude. It is assumed that the utility supply is seen as infinite bus with respect to the individual inverter. Therefore, the inverter injected signal is not expected to disturb the network while connected to the utility supply. Depending on the strategy employed, refer to section 5.1, it will then check if the injected signal has caused the network disruption (i.e. pushed the network out of the operating range) or not. If the disruption is caused then the inverter will disconnect itself from the network assuming the utility supply has been lost. Otherwise, the inverter will remain connected and repeat the same process.

In passive method, it is assumed that the loss of utility supply will cause a disruption that will push the network out of the operating range and the inverter should detect such disturbance and disconnect its self as well. In this method the inverter does not inject any disturbance signal; it merely depends on the network natural interruption events.

The design principle of these two anti-islanding methods is illustrated in the flow chart in Figure 6 below.

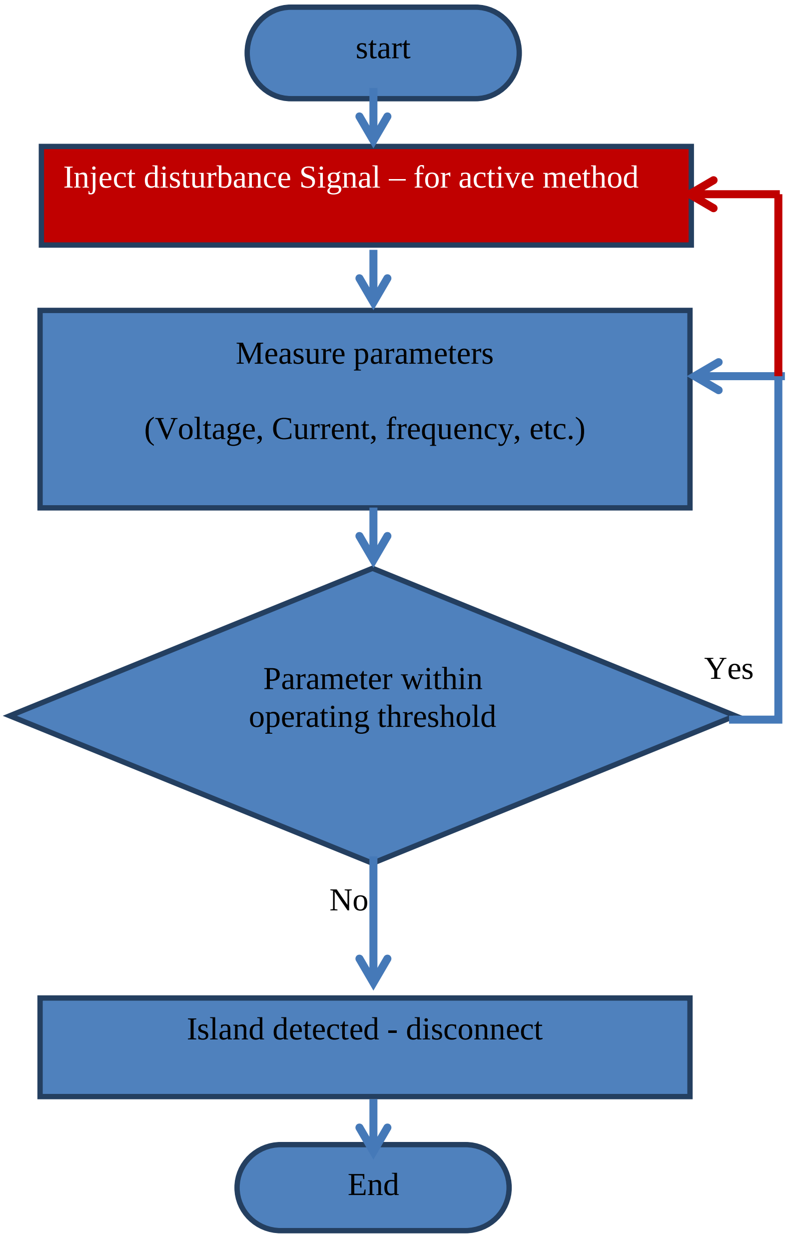

Figure 6: Anti-Islanding Flow Chart [14]

Figure 7 shows a summary of anti-islanding detection strategies that will be analysed in this thesis. There are four anti-islanding strategies that will be analysed, two active methods and two passive methods.

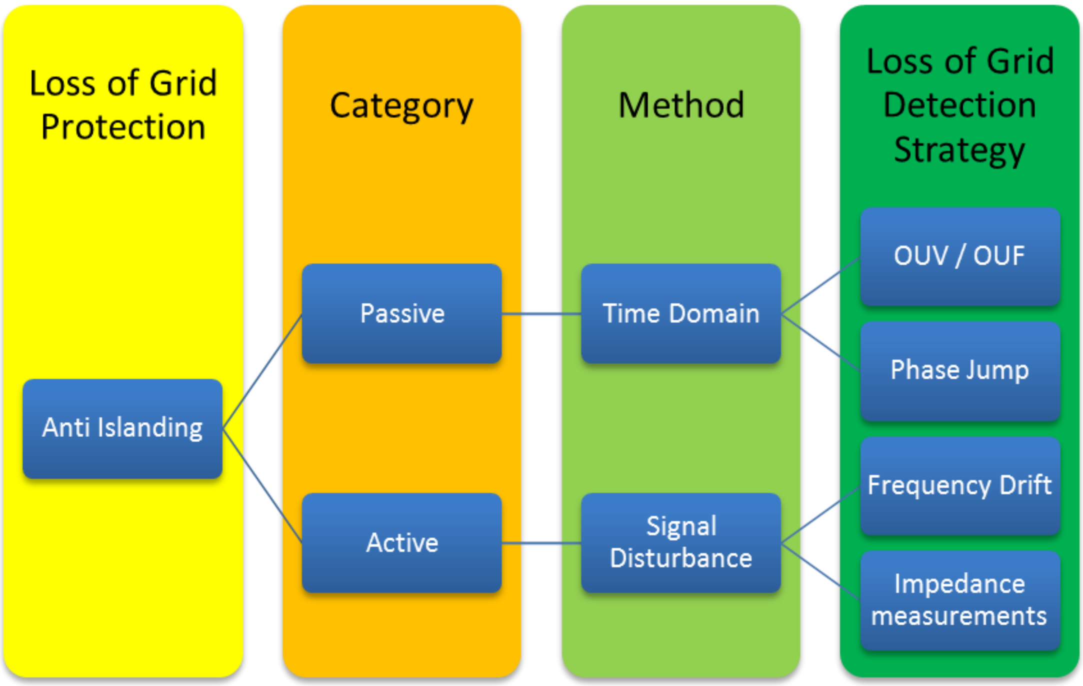

Figure 7: Anti-Islanding Methods

5.1 Loss of Grid Detection Strategies

This sub-section gives an overview of some of the strategies used to detect loss of a Grid (Utility Supply) to prevent islanding. A discussion of their modes of operation, and of their strengths, weaknesses and possible non-detection zones is also provided. The anti-islanding detection methods are established based on monitoring the voltage, frequency and phase angle at the EG interconnection point (i.e. PCC). Once the magnitude of either one exceeds a pre-specified threshold value, an islanding condition is declared and the EG is disconnected.

As a minimum requisite, grid-tied inverters are mandatory to protect against a Network Island using under / over frequency protection (U/OFP) method and under / over voltage protection (U/OVP) method to stop generating when the utility supply is disconnected. Over and above the (U/OVP) and (U/OFP), inverter may have other anti-islanding islanding detection methods as depicted in Figure 8 [3] and it will be discussed in the next sub sections 5.1.1 through to 5.1.4.

Generally, Inverters synchronises the phase of the grid signal using a phase locked loop (PLL) [15] by tracking when the signal crosses zero volts. Once the grid frequency and voltage phase angle are known it then generates a similar sine shaped voltage waveform output by varying the current output of the circuit through PWM [15].

5.1.1 U/OVP or U/OFP

The U/OVP U/OFP method relies on monitoring the voltage and frequency at the EG interconnection point. Once the magnitude of either one (voltage and frequency) exceeds a pre-specified operating threshold value, then the EG is disconnected [16]. This is a minimum requirement for all grid-tied inverters. Additional to that, the inverter may have another mechanism of detecting an Island as illustrated in Figure 8 below

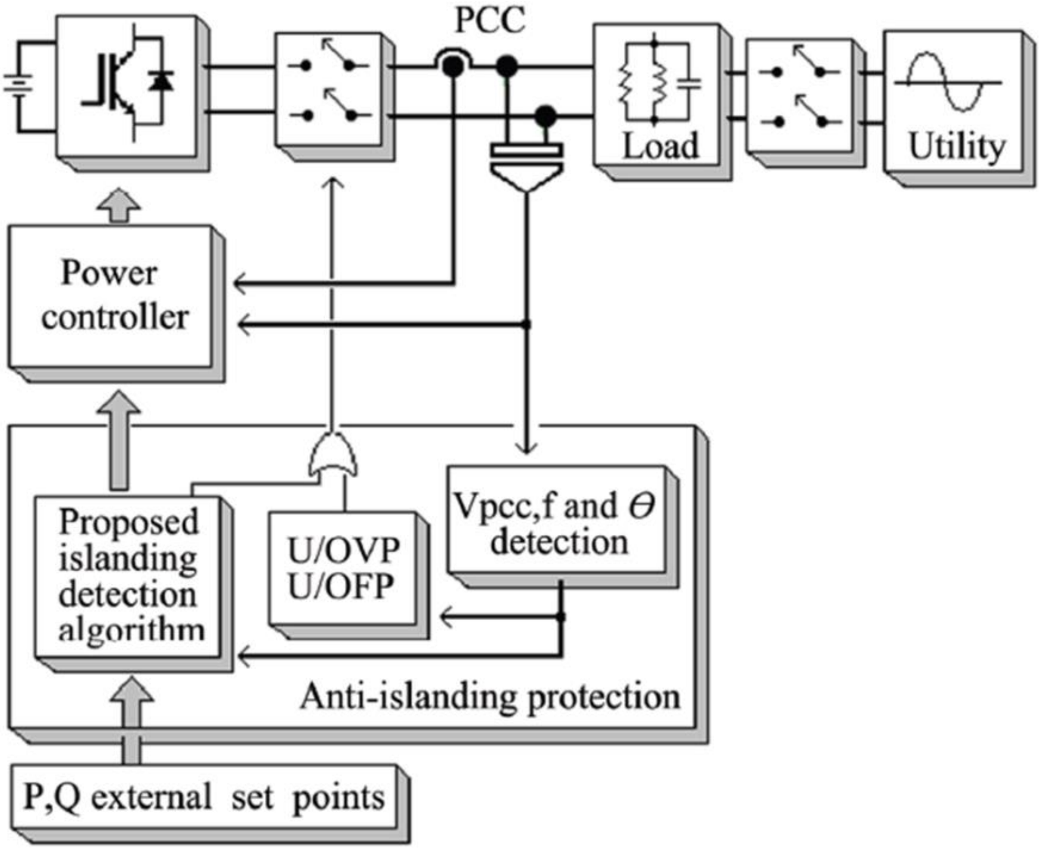

Figure 8: Block Diagram of Anti-Islanding Detection Method [17]

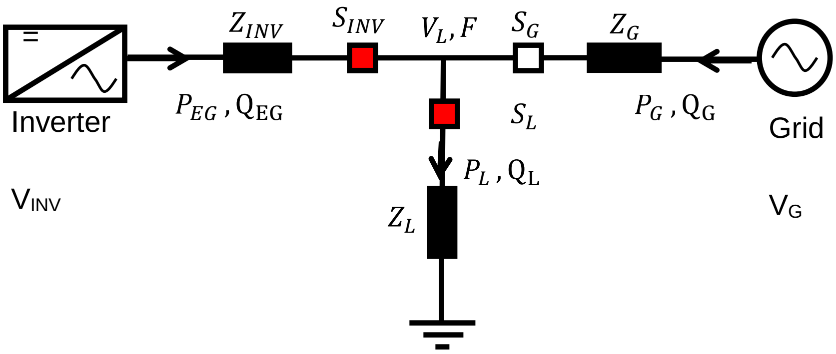

Figure 9: Grid Tied Inverter Configuration

$$P_G = P_L - P_{EG} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (3)$$

$$Q_G = Q_L - Q_{EG} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(4)$$

Where,

- P_{EG} is the real power from the inverter
- Q_{EG} is the reactive power from the inverter
- P_L is the real power of the load
- Q_L is the reactive power of the load
- P_G is the real power from the Grid
- Q_G is the reactive power from the Grid
- V_L is the load voltage

The behaviour of the system at the time of utility disconnection will depend on P_G and Q_G (grid power) at the instant before the switch opens to form the island. For example if P_G and Q_G are zero then it implies P_{EG} and Q_{EG} and P_L and Q_L are equal, respectively. After the disconnection of the grid, the active power of the load is forced to be the same with the power generated by the PV system; hence the grid voltage changes based on equation 9 below [18]:

$$\boldsymbol{V'_L} = \sqrt{\frac{P_{EG}}{P_L}}V_L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(5)$$

The above equation is true for restive loads, constant impedance load types. If the load type is constant current then equation 5 becomes:

$$\boldsymbol{V'_L} = \frac{P_{EG}}{P_L}V_L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(6)$$

For a combination of loads, constant current and constant impedance types, the resultant voltage will be somewhere in between equation 4 and equation 5, represented as follows:

$$\boldsymbol{V'_L} = \sqrt[\propto]{\frac{P_{EG}}{P_L}}V_L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(7)$$

Where, $1 < \alpha < 2$, depending on the percentage mix of the loads

For constant power load types, P_{EG} has to be exactly equal to the load, P_L, otherwise the system will collapse on over-voltage or under-voltage. If P_{EG} is greater than P_L, V_L will rise and vice versa.

For a combination of loads, constant current and constant power types, the resultant voltage will be defined as follows:

$$\boldsymbol{V'_L} = \sqrt[\propto]{\frac{P_{EG}}{P_L}}V_L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(8)$$

Where, 2 < α < 1, depending on the percentage mix of the two loads

This condition is unlikely to occur in residential areas because most of the residential big loads are resistive, constant impedance, such as stoves, geyser, heaters, kettle, etc.

Just before the utility breaker opens to form an island, if the power (i.e. active and reactive) generated P_{EG} and the load P_L are balanced then during islanding the frequency will drift closely around the nominal frequency and the voltage at PCC will remain unchanged. However, if the power is unbalanced then both voltage and frequency will drift and the U/OVP U/OFP may detect the change in voltage and frequency and prevent an island.

If the PV generation is greater than the local load, both voltage and frequency will rise and if the PV generation is less than the local load, both voltage and frequency will decrease.

If there is a big mismatch between generated power and loads, islanding will not occur. This covers the vast majority of practical cases [6]. Normally reactive power component is very small in a residential environment and sometimes zero.

Thresholds for the four U/OVP U/OFP protection devices cannot be set arbitrarily small otherwise the PV inverter will be subjected to nuisance trips [6], however large threshold result in large non-detection zone (NDZ). Therefore, this anti-islanding method is not reliable, it may not detect loss of supply when mismatch between PV and loads are small. Although it has other advantages such as good on power quality and it is not affected by parallel operation of inverters like other methods that will be discussed later in the section.

5.1.2 Phase / Voltage Jump

Phase jump detection (PJD) involves monitoring the phase difference between the inverter’s terminal voltage and its output current for a sudden "jump" [6], if the sudden jump in phase angle is larger than the threshold, the inverter will be shut down or de-energized. The size of the phase jump will be affected by the power factor of the load.

A non-detection zone (NDZ) may exists when the load has a zero phase angle (i.e. unity power factor). Depending on the threshold, this NDZ can be smaller than the NDZ of U/OVP U/OFP protection method.

Voltage angle at the terminal of EG busbar depends on the system impedance the EG is connected to. If the utility supply is removed the voltage angle is expected to change quickly and the phase angle between voltage and current of the PV inverter is also expected to change as illustrated in Figure 10, Figure 11, Figure 12 and Figure 13.

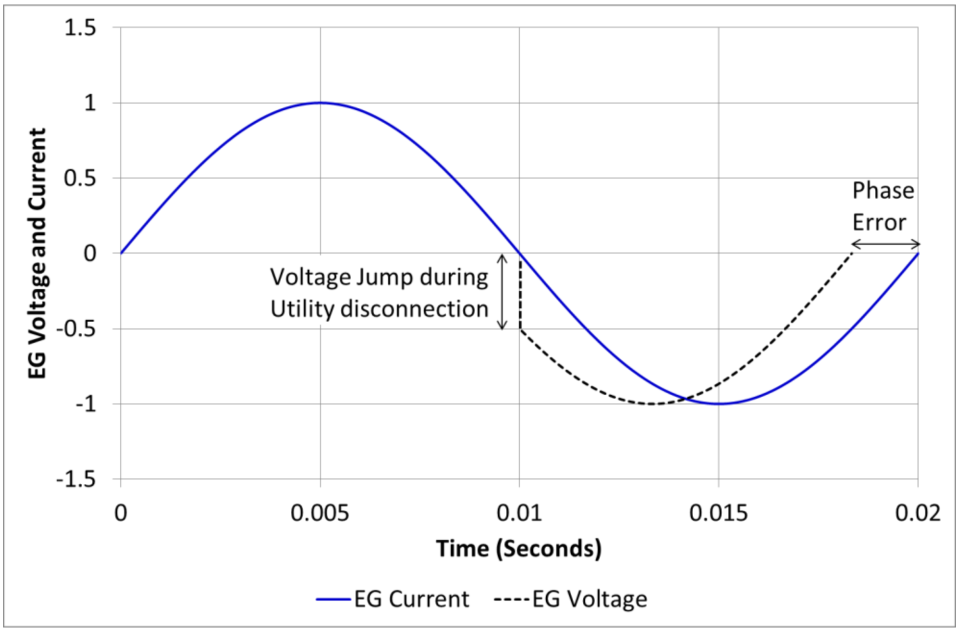

Figure 10: Voltage Jump and Phase Error during Utility Disconnection [14]

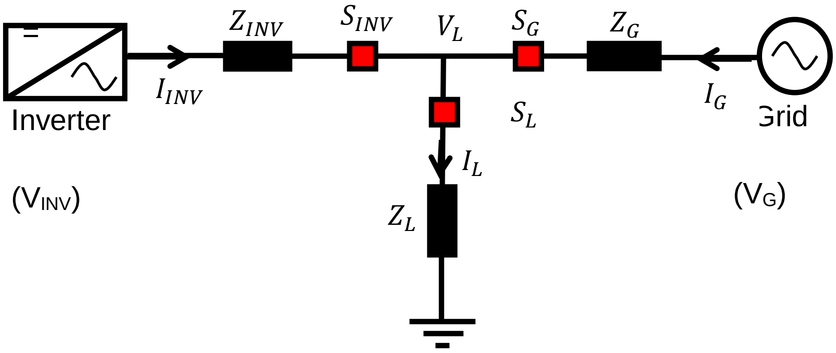

Figure 11: Loss of a Grid

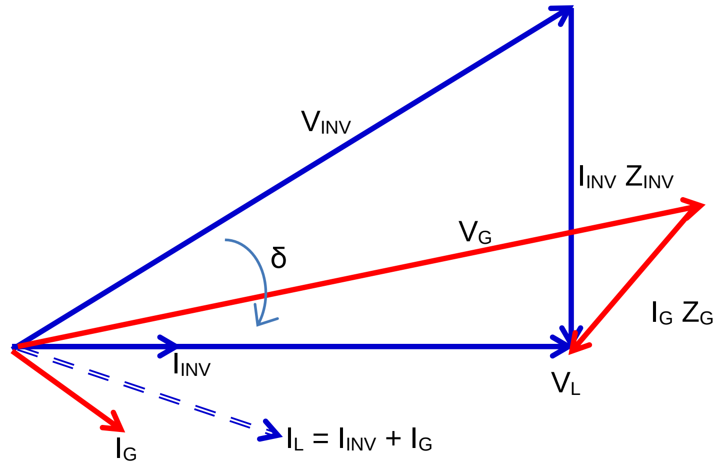

Figure 12: Phasor Diagram When EG is Synchronised with the Grid [19]

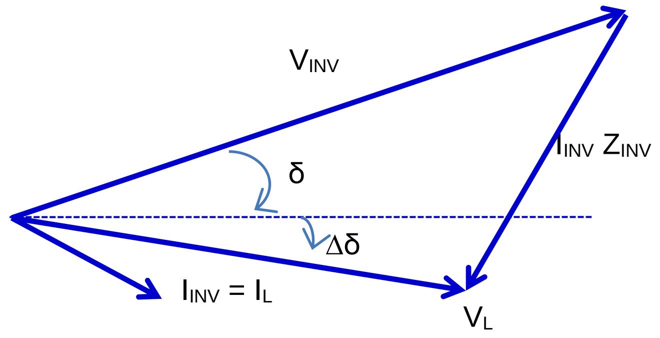

Figure 13: Phasor Diagram after Loss the Grid [19]

Where,

- δ is the voltage angle between the load voltage and the inverter voltage
- Δδ is the vector shift angle

Ideally Loss a grid (strong source) will result in the following:

- voltage change if load and generation are not balanced
- Load power factor will remain unchanged
- Inverter current phase angle will change to match that of the load
- Current magnitude of the load will be equal to that of the Inverter (EG)

Basically, inverter current phase jump will always be influenced by the power factor of the load. The main benefit to this method is that the shift in phase will always occur even if the

PV power matches exactly local load / load within an islanded network. Non-detection zone (NDZ) occurs when there is a unity power factor which is very unlikely to happen. The downside is that load with large power factor like motors starting also cause phase jumps which may require use of large protection threshold which may reduce its effectiveness. However, this is very rare in residential areas / networks. Also, this method, does not affect power quality of the network and it is not disturbed by other parallel connected inverters on the same network.

5.1.3 Frequency Drift / shift / bias

Frequency Drift is one of the active anti-islanding methods; the PV inverter injects a disturbance into the network to force the network parameters such as voltage magnitude, frequency, etc., to deviate from the normal operating point. It assumes that the entire network seen by the PV inverter is an infinite busbar and will only be pushed outside normal operating point by the PV inverter only during an island condition [20].

The Frequency Bias anti-islanding method forces a slightly off-frequency signal into the grid, but "fixes" this at the end of every cycle by jumping back into phase when the voltage passes zero [15]. This is illustrated in Figure 14 below.

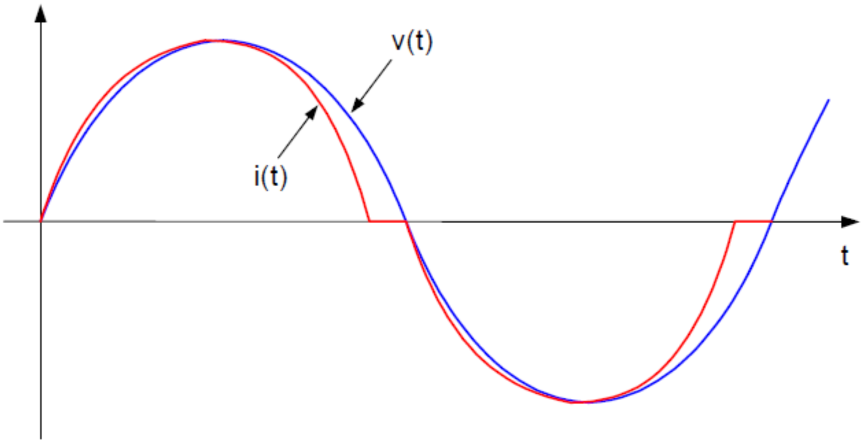

Figure 14: Frequency Bias Method [4]

It is expected that the grid (infinite busbar) will not be affected by the PV inverter signal during system healthy or normal condition however the frequency will drift away from the normal operating frequency, eventually causing the PV inverter to shut down [21] when the grid is disconnected.

The downside is that if there are several inverters connected in parallel, all inverter have to be synchronised to shift the frequency signal simultaneously otherwise each inverter will force the signal in different directions and dilute the resultant effect. This dramatically reduces the chance of detecting an island.

5.1.4 Impedance measurements (Power Shift)

Like the Frequency Drift, Impedance Measurements or Power Shift is also an active anti-islanding methods; the PV inverter injects a disturbance into the network to force the network parameters to deviate from the normal operating point when the grid is disconnected. Also, it assumes that the entire network (grid) seen by the PV inverter is an infinite busbar and will only be pushed outside normal operating point by the PV inverter only during an island condition [20].

Impedance Measurement attempts to measure the overall impedance of the circuit being fed by the inverter [21] by injecting disturbance current at a specified (frequency) and magnitude. It is recommended that the injected disturbance should not be more than 20% of the maximum output current [6]. This will have no effect on the system as long as the grid (infinite busbar) is connected. Once the grid is disconnected, then the injected disturbance would result in a significant change in frequency, voltage or phase angle, allowing detection of the island [21]. The advantage of this method is the small NDZ for a single connected inverter however, if multiple inverters (especially of different make and type) are connected in parallel configuration there will be a dilution effect due to lack of synchronisation or coordination. In such configuration (i.e. parallel), each inverter will recognise other parallel connected inverters as infinite busbar reducing the chance of detecting an island.

This method only works for a single inverter and if the grid is effectively infinite.

5.2 Chapter in Perspective

In this chapter, there are four anti-islanding detection methods that have been presented. These methods can be classified into two groups, namely: passive and active techniques. In the first group the detection the following conclusion can be drawn:

- This thesis has demonstrated that there is a high risk of anti-islanding failure of U/OVP U/OFP detection method but its performance improves as the load and generation unbalance increases. It is anticipated that the risk will be small during low level of PV penetration to the LV Utility network.
- Phase or Voltage Jump Method is one of the best anti-islanding detection method especially on networks with power factor of less than one. It can be used even on networks with multiple inverters of different type connected in parallel. The phase

jump method is highly recommended for South African networks as it is simple and cheap to implement.

Whereas in the second group, the following conclusion can be drawn:

- Both Frequency Drift / Shift / Bias and Impedance Measurement methods have a very small non-detection zone for a single connected inverter but its performance and effectiveness get reduced as the number of parallel connected inverters increases thus it is not recommended for parallel operations and to be used in Eskom LV networks in order to reduce risk of anti-islanding.

Therefore, if active methods are used in the network, the operator should ensure that load and generation within a possible island are highly unbalanced in order to rely on U/OVP U/OFP detection method for protection as this is required to all types of inverters otherwise active methods are prone to failure in parallel operations. Also use other strategies such as inter-tripping schemes and smart grid technology to avoid a Network Island is recommended. Furthermore, the passive methods do not disturb the network, (i.e. no power quality impact) but have high NDZ which is a risk for islanding. On the other hand active methods have both, high power quality degradation impact and high NDZ when connected in parallel. This makes the Passive (Phase Jump) method more favourable in all aspects.

Chapter 6: EG Anti-Islanding Failure Modes Analysis [22]

The South African Network Grid Code does not allow any generator to island any portion of the network [1]. Hence, South African LV networks are not designed to island, if an island occurs it is considered as illegal operation. Therefore, embedded generators are required to disconnect immediately after a loss of utility supply. However, it is anticipated that anti-islanding protection may fail under certain generation and loading conditions and cause an LV Network Island. Based on the current LV network design, the Network Island may possibly occur in one of the zones as depicted in Figure 15.

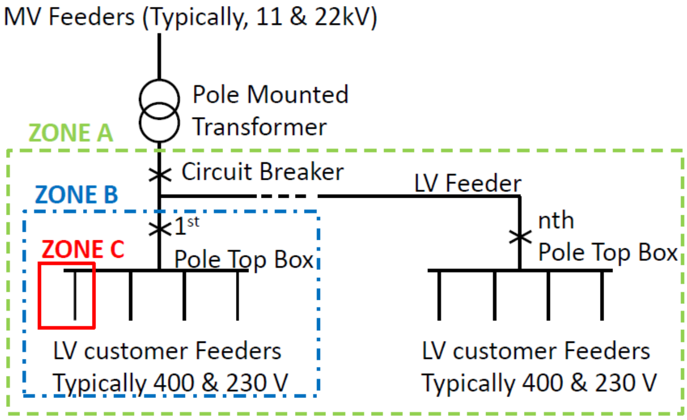

Figure 15: Network Islanding Zones

Normally, electrical loads are located in zone C as shown in Figure 16 below.

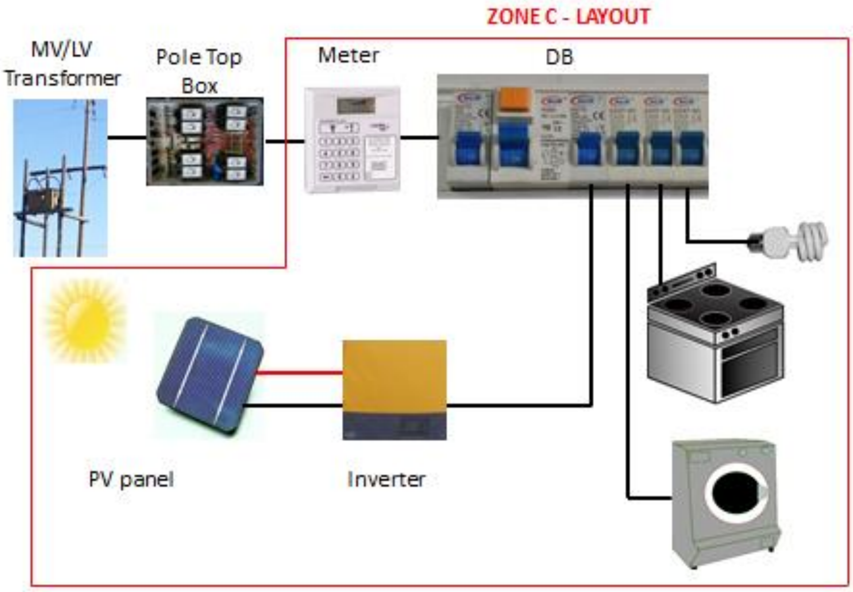

Figure 16 Typical Layout Within Zone C of Residential Network

Basically, there are three possible islanding zones in an LV network with Embedded Generation (PV inverters), namely:

- Zone A – is at the transformer zone where the MV/LV supplies several pole top boxes
- Zone B – is at the pole top box or underground distribution kiosk. Typically, a pole top box or an underground kiosk supplies four LV customers via a single circuit breaker.
- Zone C – is at the customer service cable zone where the embedded generator is directly connected via a DB of the house.

The risk of anti-islanding failure differs per zone. It is anticipated that Zone B will perform poorly compared to other zones due to the following anti-islanding failure prerequisite / pre-conditions that are likely to occur in zone B:

- Power balance – when power generated by Embedded Generator is equal to the customer load within a zone, i.e. both active and reactive power.
- Parallel operation of grid tied inverters of different design, make and type

This is further elaborated in the next section.

6.1 Risk of Power Balance (Match between Generation and Demand)

The power supply and demand could be balanced in a zone due to the following three mechanisms:

- Power export limiting or prevention (some EG are design not to export power to the grid)
- National Requirements Specification, NRS 097-2-1 [3], maximum generation requirement being equal to the customer demand (i.e. After Diversity Demand [ADD])
- Voltage and frequency dependency of Loads [23]

6.1.1 Power Export Limiting or Prevention

Some of the grid tied-inverters are designed to throttle their output via energy meter to avoid power export. This is because the current billing system does not support or compensate customers that are generating to the grid. Such designs are high risk with respect to power balance match and can lead to anti-islanding failure. The risk is approximately eight hours during the day between 9h00 and 17h00 as depicted in Figure 17. Power throttling could start as early as 10h00 to 14h30 in the afternoon where generated power is 100% balanced with the load demand.

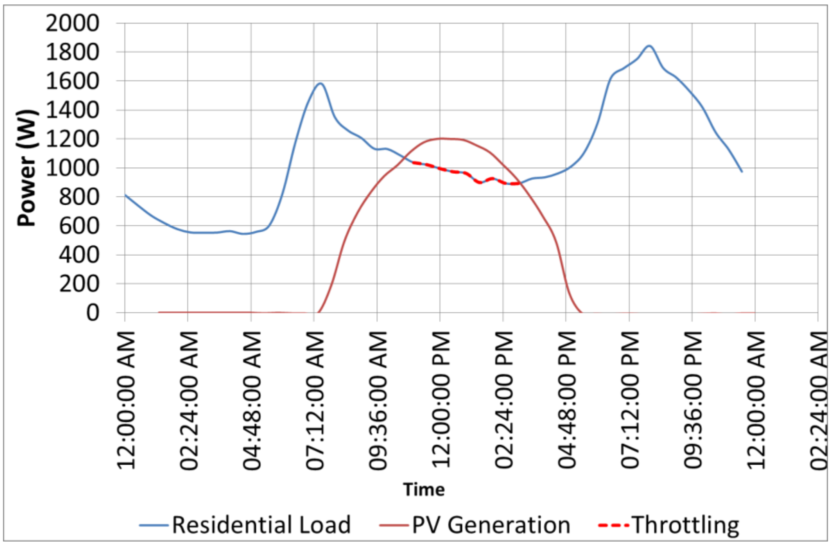

Figure 17: Power Export Limiting or Prevention [22]

6.1.2 EG Statutory Requirement vs Actual Load

As stated above, NRS 097-2-1 [3] requires a single phase 20A installation to have a maximum embedded generation of 1200W at a unity power factor [3]. The ADD for such installations is typically around 1000W during PV generation peak as shown Figure 18. Therefore, this statutory requirement poses a serious risk of anti-islanding failure especially during PV peak generation. The load and generation mismatch is very small, (in this case of Figure 18, around 200W) and this small power mismatch margin is expected throughout the year, i.e. all seasons and weekdays. The same risk applies to other LV customers, large power users. LV customer segments are shown in Table 4. The analysis in this thesis is performed on one customer category, small power users, assuming that other categories, medium and large customers will yield same results.

Table 4: Customer Segments [1], [3]

Customer Segment	Class	Capacity Limit (Based on MCB Amp Rating)
Small Power Users (Small Generators)	A1 (0.1 to 13 kW)	• 20 A , 1.2 kW single phase • 60 A, 3.45 kW single phase • 80 A, 4.6 kW single phase
	A2 (13 to 100 kW)	• 60A and 80A, 13.8kW three phase
Large Power User (Large Generators	A3 (100 to 1000 kW)	• Not applicable

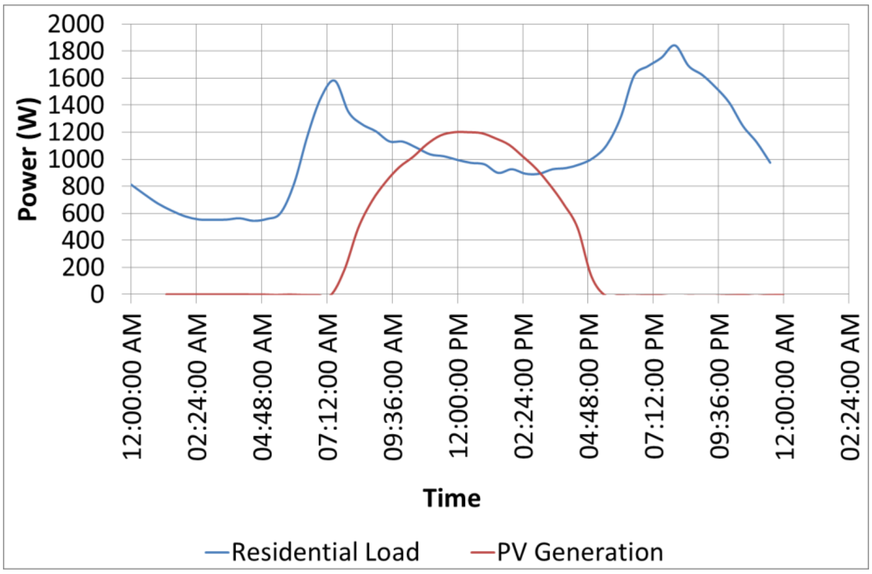

Figure 18: Statutory vs Actual Load [22]

6.1.3 Voltage and Frequency Dependency of Loads

In a power system network there are various loads / appliances connected simultaneously at any point in time. Each appliance has a unique voltage and frequency dependency characteristics, i.e. the amount of power being consumed by an appliance vary with voltage and or frequency at any given point in time. This relationship is defined by the following equations [23], [24], [16], [10], [25]:

$$\mathrm{P}(V,f) = P_o\left(\frac{V}{V_o}\right)^{\alpha}\left(\frac{f}{f_o}\right)^{\varphi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (9)$$

$$Q(V,f) = Q_o\left(\frac{V}{V_o}\right)^{\beta}\left(\frac{f}{f_o}\right)^{\gamma} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(10)$$

Where:

P_o - is the real power of static load before disturbance (i.e. initial condition)

Q_o - is the reactive power of static load before disturbance

V_o and f_o - are the rms voltage amplitude and frequency disturbance, respectively

V and f - are the rms voltage amplitude and frequency under operating condition, respectively

α,φ,β and γ - are the partial derivatives of the real and reactive power of static load with respect to the voltage and frequency near the initial condition, respectively

The rate of change of the real power with respect to voltage α value predicts how that particular loads magnitude kW will vary with a change in service voltage. The greater the positive magnitude of α the more that load's kW magnitude will decrease as its service voltage decreases [23]. If the initial condition, before utility supply is lost, is such that the load real power is greater than the PV generation then upon the loss of utility supply the load real power will decrease up to a point of equilibrium where the PV generation is equal to the load demand. Also if the point of equilibrium is reached while the voltage is still with the normal operation limit then the Network Island will probably occur. Likewise with φ, the kW load magnitude will vary with frequency. Lastly, β and γ predicts how kVars load magnitude will vary voltage and frequency respectively. If any of the four exponents is negative then process is the inverse i.e. a drop in voltage or frequency will lead to an increase of load magnitude.

In order to demonstrate this phenomenon various domestic appliances such as fridge, Compact Fluorescent Lamp (CFL) and incandescent light bulb were tested at the lab. This is based on a typical residential load mix as shown below.

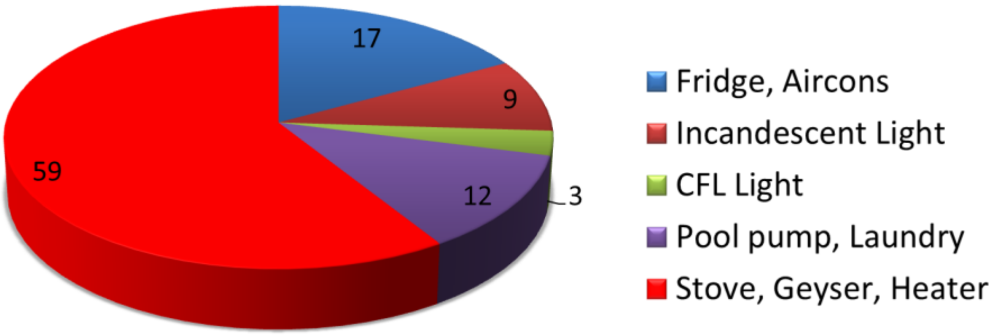

Figure 19: Residential Load Mix [22]

Figure 20 and Figure 21 shows results of voltage dependency of a fridge and incandescent lamp that was tested, the rest of the results are tabulated in Table 5.

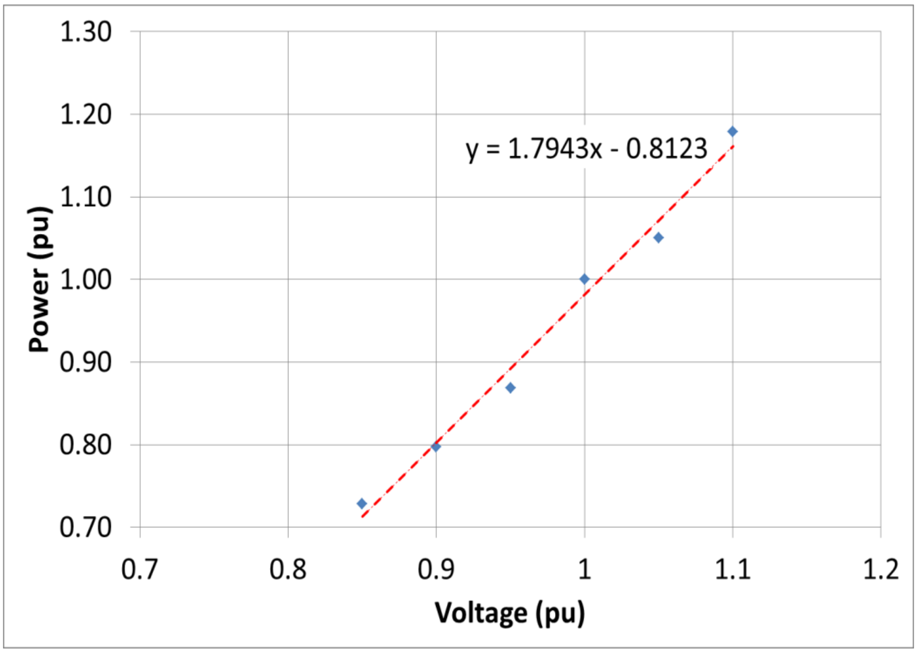

Figure 20: Effect of voltage variation on a fridge load magnitude [22]

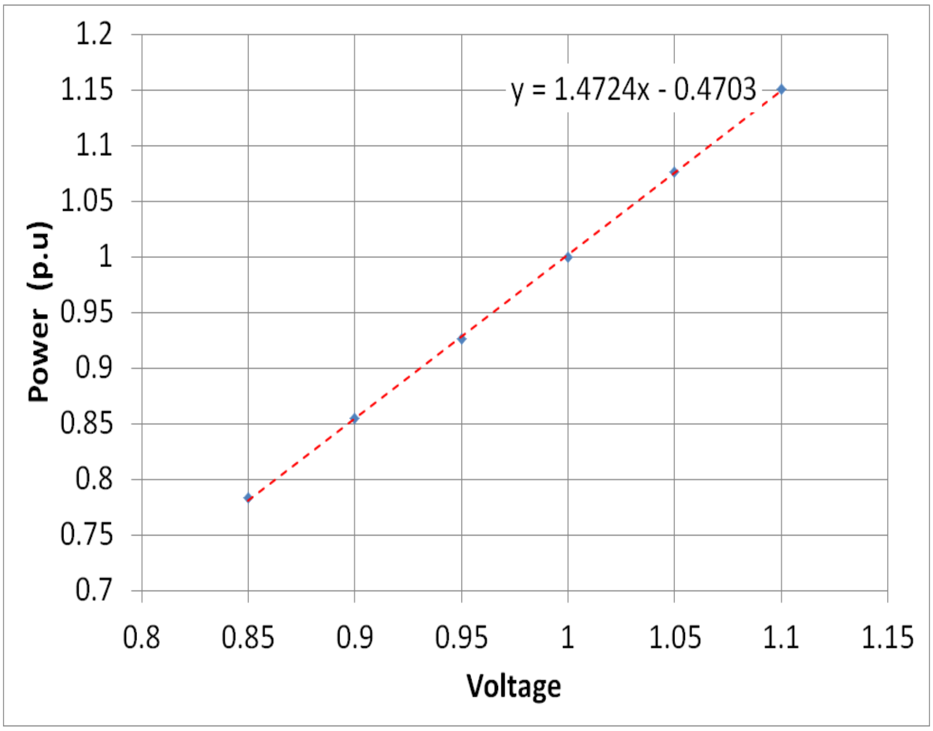

Figure 21: Effect of voltage variation of an Incandescent Light load magnitude [22]

Table 5: Voltage and Frequency dependency of Residential Appliances

Appliance Type	**Voltage Dependency**		**Frequency Dependency**	
	α	φ	β	γ
Fridge, Air conditioner	1.79	-1.26	1.79	-1.26
Incandescent Light	1.47	0	0	0
CFL Light	0.25	3.16	0.1	-2.5
Pool pump and Laundry	0.2	2.5	3.0	2.2
Stove, Geyser, Heater	2.0	0	0	0

6.1.3.1 Load Aggregation [26], [27]

Based on the voltage dependency of individual appliances and the residential load mix, a composite load model can be established by combining all equations to form one that represent a combined effect of all appliances (aggregated load model) on the LV network. The aggregated load model is derived using DigSilent Powerfactory load flow analysis. A combine load response analysis is performed by splitting 1MW proportionally according to Figure 19, load mix. This is then simulated in DigSilent Powerfactory as shown in Figure 22. Initially, before loss of grid, the load is fed at one p.u voltage with the grid supplying 10% (0.1MW) of the total load and the PV supplying 90% (0.9MW). When the grid is disconnected, the simulation shows that the voltage is reduced to 0.94 p.u as shown in Figure 22. The calculated 0.94 p.u voltage is then utilised to estimate voltage dependency factor using voltage dependency curve in Figure 23. Voltage dependency curve in Figure 23 was plotted using the following equation and assuming 10% load mismatch.

$$\mathrm{P}_{EG} = P_L \left(\frac{V}{V_o}\right)^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (11)$$

Where:

P_{EG} is the Embedded generation

P_L is the actual load

α is voltage dependency factor

V_o is the initial voltage before loss of a grid and it is assumed to be 1 in this example.

From equation 11, voltage was calculate for various values of α as shown in Figure 23

$$V = \left(\frac{P_{EG}}{P_L}\right)^{\frac{1}{\propto}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (12)$$

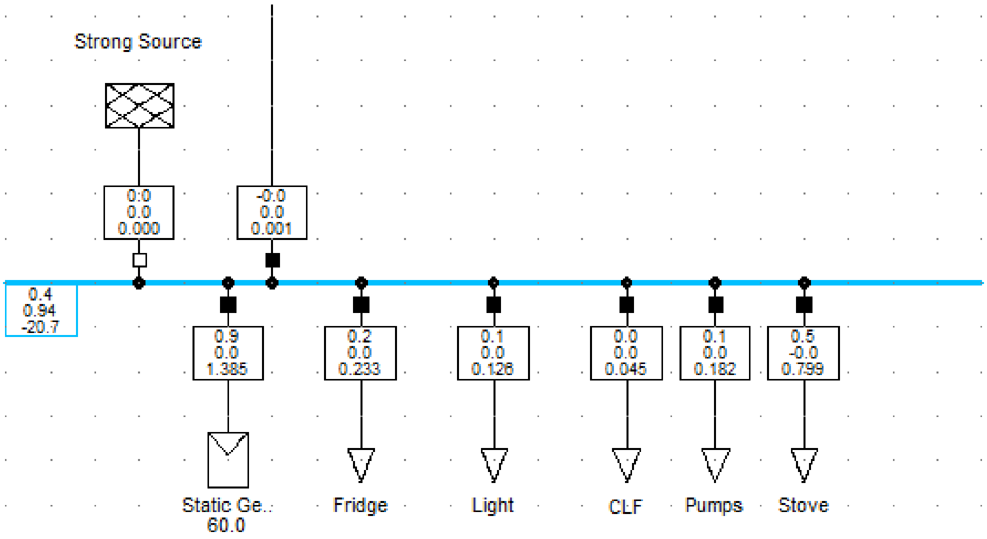

Figure 22: Aggregation of Residential Loads Calculation

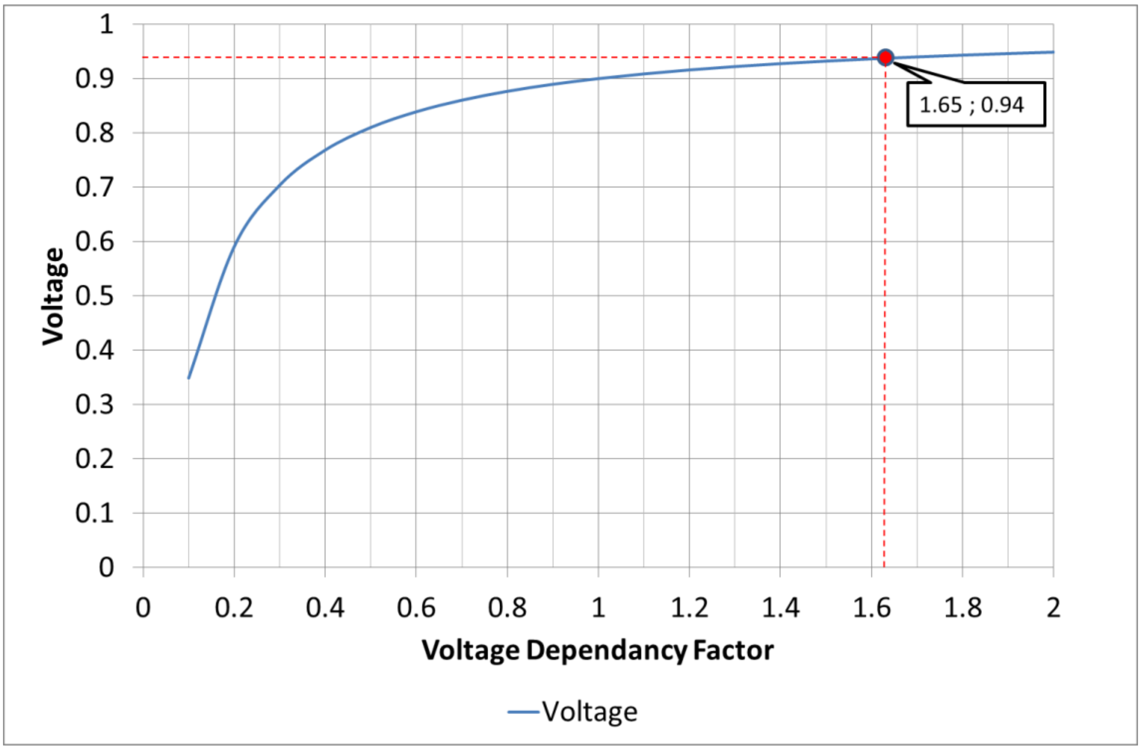

Figure 23: Voltage Variation for various voltage dependency factor

The estimated voltage dependency is 1.65. The same methodology was applied to estimate other aggregated load model parameters and the results are as shown in Table 6 below.

Table 6: Composite Load Model of Residential Customers

Appliance Type	Voltage Dependency		Frequency Dependency	
	α	φ	β	γ
Fridge, Air conditioner	1.79	-1.26	1.79	-1.26
Incandescent Light	1.47	0	0	0
CFL Light	0.25	3.16	0.1	-2.5
Pool pump and Laundry	0.2	2.5	3.0	2.2
Stove, Geyser, Heater	2.0	0	0	0
Composite Load Model Parameters (Aggregated Parameters)	1.65	0.18	0.67	-0.003

Now, applying the above results to equation 9 and assuming the PV is generating 850 W at 1.pu Volt and the Load is 1,100 W as` depicted in Figure 24. Then should a utility supply be lost, the final load voltage will be as follows:

$$P(V,f) = P_o \left(\frac{V}{V_o}\right)^{\alpha} \left(\frac{f}{f_o}\right)^{\varphi}$$

$$850 = 1100 \left(\frac{V}{1}\right)^{1.65} 1$$

V = 0.86 as shown in Figure 25

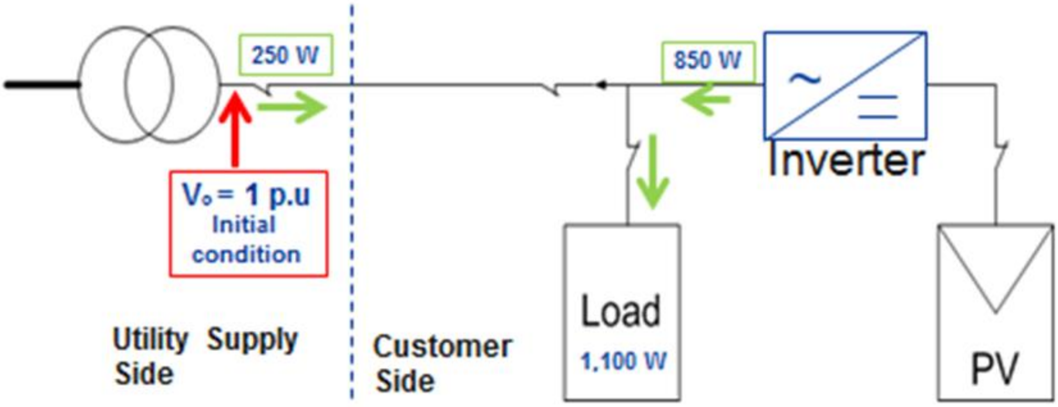

Figure 24: Study Case – Before Loss of Utility Supply [22]

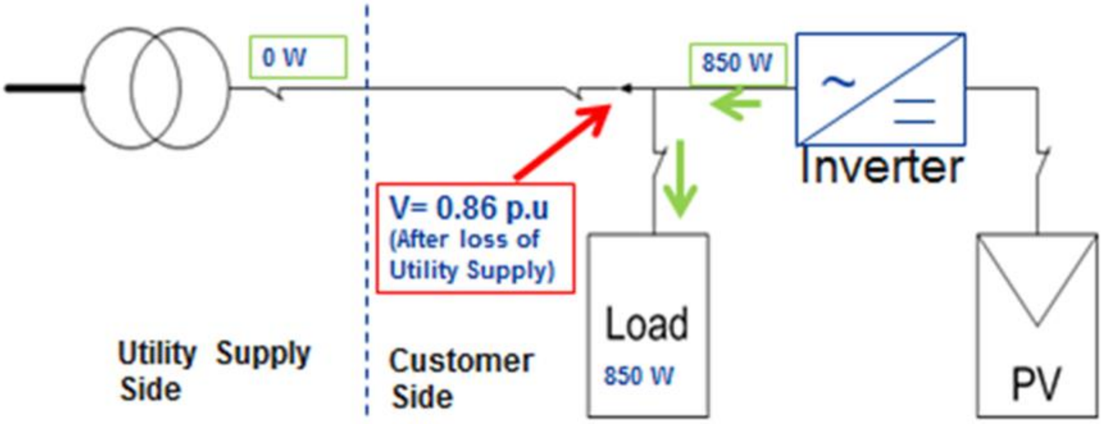

Figure 25: Study Case –After Loss of Utility Supply [22]

Therefore, a mismatch of 250W (i.e. equivalent to 28% of embedded generation) results in an anti-islanding failure since it is within operating voltage threshold of -15% as stipulated in the grid code [1].

Some of the grid-tied inverters use active method such as Impedance Measurement, which continuously changes the current output magnitude of the inverter by 20% to detect an island. The above example has demonstrated that a disturbance of 250W (i.e. 28%) may result in anti-islanding protection failure. It is therefore evident that both passive and active inverter types are prone to anti-islanding failure protection in residential area.

High-risk region of anti-islanding or non-detection zone is between 9h00 and 17h00 as shown (i.e. highlighted in red) in Figure 26 where mismatch is 250W and below. The risk of anti-islanding failure for PV inverters is approximately eight hours during the day.

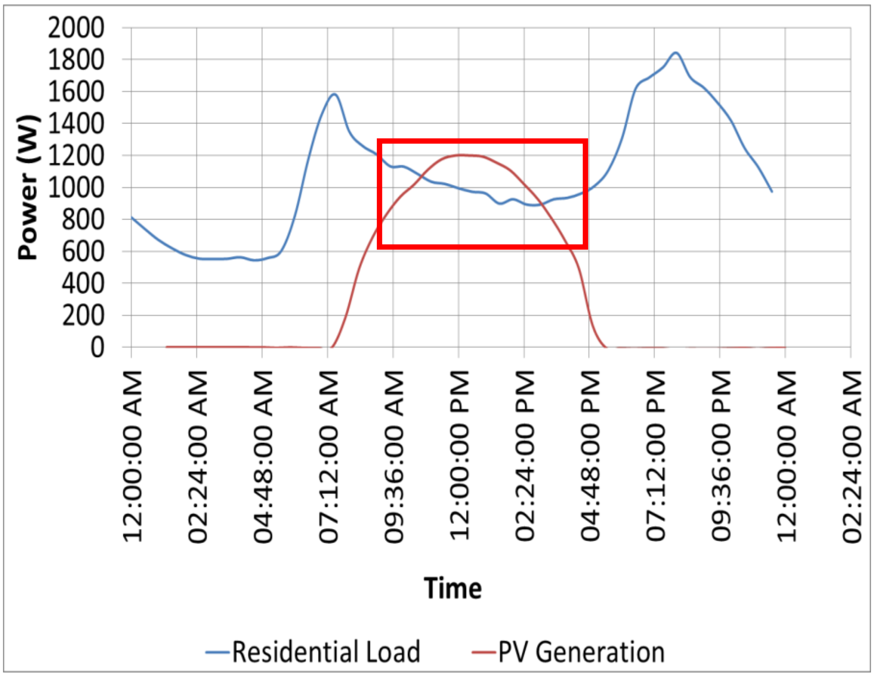

Figure 26: Risk of Anti-Islanding Failure on Residential Loads [22]

Other literature argued that the likelihood of an islanding is very low if 100% power match is assumed; in practice it might not be a serious concern [7]. However, there are different opinions that an island can be formed without 100% power matching as demonstrated above the power mismatch could be up to 20%. Therefore, NDZ for residential load is within 20% power mismatch.

6.2 Parallel operation of grid tied inverters of different designs

It is important to understand different types of inverter designs and the requirement for parallel operations.

In addition, if there are many EGs connected in parallel the risk of anti-Islanding is high also. The active anti-islanding protection schemes, such as Impedance Measurements, frequency Bias, etc. may work for a single connected EG, but may not work for EGs connected in parallel within an operating zone. If active anti-islanding protection method are connected in parallel, different inverters may generate disturbance signals that are out of phase which may cancel each other unless they are synchronised which is not always possible. The out of phase signals are illustrated in Figure 27. Therefore, this type of inverters has performance issues when operated in parallel [7], [5].

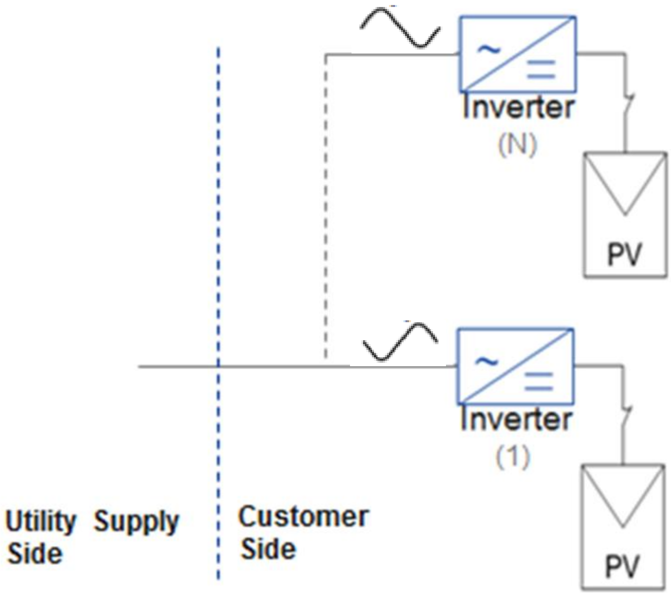

Figure 27: Risk of Anti-Islanding Failure due to parallel operations of inverters

6.2.1 Measurement on Eskom Rosherville PV Plants

Eskom has installed PV plants at Rosherville offices which has several SMA inverters units of 15 kW each, connected in parallel. The Rosherville PV Plant was tested for anti-islanding to demonstrate the effect of connecting PV inverters in parallel. The section of the Rosherville Plant that was tested had six parallel inverters (i.e. of 15kW each). At the time of the test each inverter was supplying approximately 6kW. Before the test was performed five of the six inverters were disconnected from the grid leaving just one online generating about 6kW. The test was performed by removing the grid supply from the one remaining inverter and monitoring its out response in the process. Figure 28 shows the current and voltages during inverter shutdown. It is evident that during shut down the inverter was injecting current signals which as a result deviated phase voltage as depicted in Figure 28. The same test was repeated when all six inverters were online and the results show that the disturbance signal was no longer as visible as the first test. This does prove that multiple inverters affect one another negatively with respect to islanding detection even if they are of the same design, make and type as shown in Figure 29. For both condition, the frequency dropped below operating threshold and caused the inverters to trip.

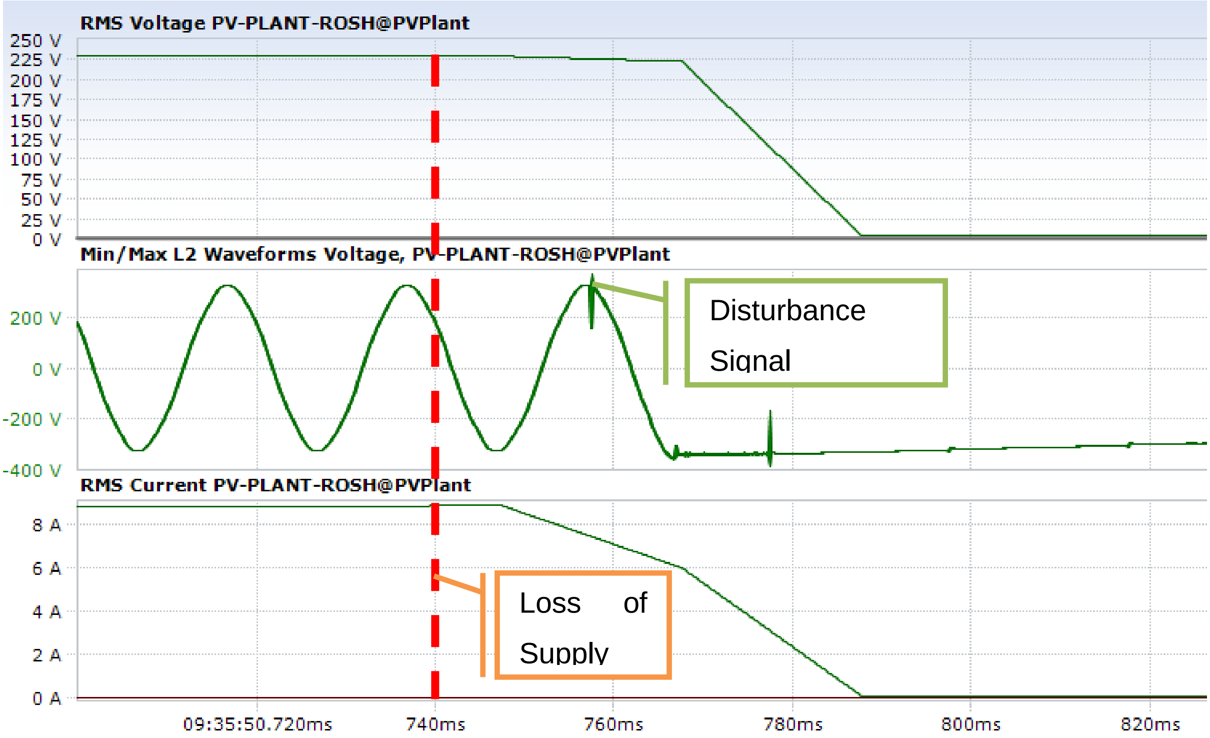

Figure 28: Single SMA Inverter at Rosherville Plant

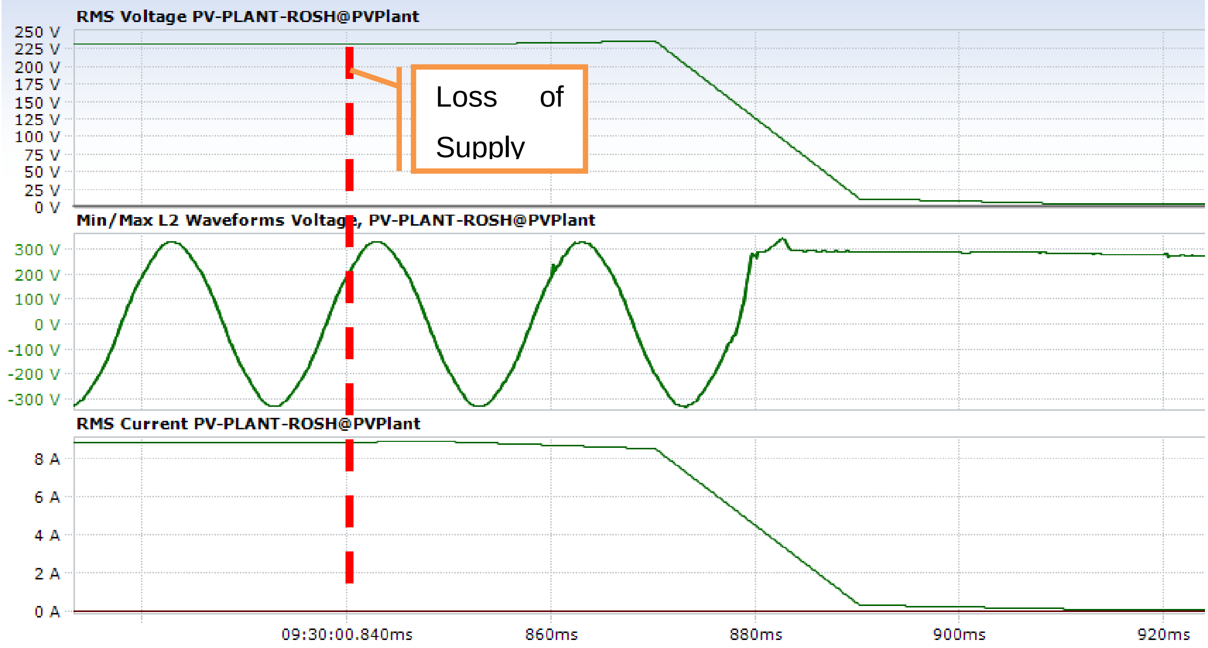

Figure 29: Multiple SMA Inverter at Rosherville Plant

6.3 Chapter in Perspective

This chapter has demonstrated that there is a high risk of anti-islanding failure of PV inverters due to high probability of load and generation balance in residential area during the day. It is difficult for the grid tied inverters to detect the loss of utility supply, especially where more than one inverter of different design, make and type exist in one zone. Therefore, it is recommended that the utility should use other strategies such as inter-tripping schemes and smart grid technology to enhance isolation of EG in the event of utility supply loss.

Chapter 7: Case Study and Analysis

The aim of the case study is to establish a wide range of operating thresholds for LV residential network based on the theory that has been covered on previous sections. A DigSilent Powerfactory model is developed to estimate NDZ when grid supply is disconnected under various load and PV inverter generation conditions. Various anti-Islanding protection methods are evaluated to establish the impact on NDZ of paralleling various combinations. The following scenarios were evaluated as listed in Table 7

Table 7: Study Case Scenarios

Scenario Number	Description
1	U/OVP for power mismatch of 10%, and for various voltage - load dependency factors
2	U/OFP for power mismatch of 10%, and for various voltage - load dependency factors
3	U/OVP for power mismatch of 15%, and for various voltage - load dependency factors
4	U/OVP for power mismatch of 20%, and for various voltage - load dependency factors
5	U/OFP for power mismatch of 20%, and for various voltage - load dependency factors
6	U/OVP for power mismatch of 25%, and for various voltage - load dependency factors
7	U/OFP for power mismatch of 25%, and for various voltage - load dependency factors
8	Impact of paralleling PV inverters with U/OVP and U/OFP methods
9	Impact of paralleling Impedance Measurement PV inverters
10	Impact of paralleling Impedance Measurement PV inverters with U/OVP and U/OFP.

DigSilent Powerfactory simulation was developed to illustrate the impact of connecting parallel the PV inverters of different design taking into account voltage dependency of loads. The study entails running several load-flow and dynamic simulations to establish performance of U/OVP and U/OFP under various loading and generation conditions for various voltage dependency factors. The previous analysis of this thesis showed that residential loads (aggregated) has about 1.65 voltage dependency factor, hence the normal operating region for residential is estimated to around this value / region.

First analysis is for when the PV inverter generation is smaller than the load. This yields under voltages when utility supply is lost. The simulation results in Figure 30 shows that there is an NDZ for under-voltage protection. Under-voltage protection of PV inverters is set at 0.85 as per requirement of the grid code [1]. Before loss of a grid, the network is operated at 1.pu voltage and the voltage drop due to disconnection of the grid. Results are summarised in Figure 30.

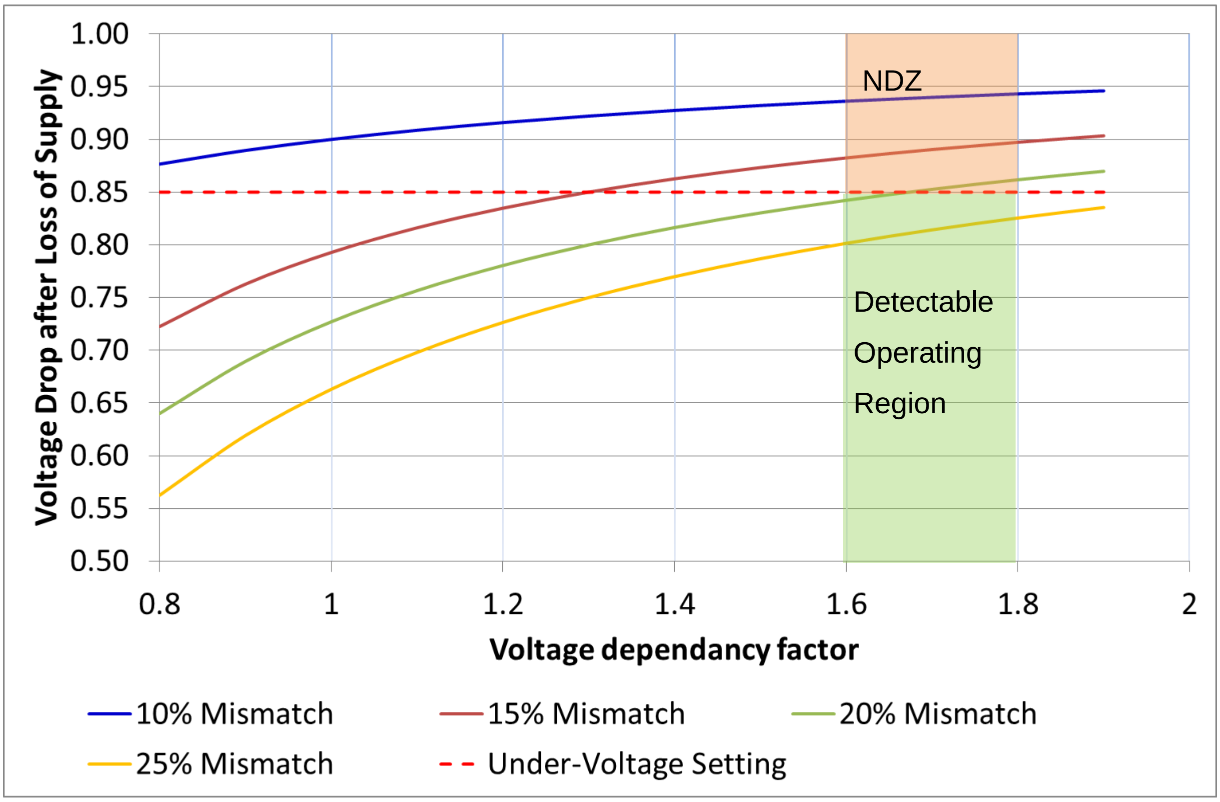

Figure 30: Voltage Drop due to Disconnection of a Grid when PV Inverter Generation is smaller than Load

In the operating region highlighted above in Figure 30, a mismatch of up to 20% is detected by Active - Impedance Measurements method but Passive – UVP method is unable to detect an Island for the same conditions. Once Impedance Measurement method is connected in parallel with are inverters, it is unable to detect loss of supply due to the fact that the injected signal is much smaller with respect to the total generation in an islanded network. A maximum of 20% of individual inverter is not enough to cause disturbances in the system especially when the inverters (i.e. Impedance Measurements) are not synchronised.

A similar study is performed for over-voltage anti-islanding protection. If the grid is disconnected when PV inverter generation is higher than the local load, overvoltage occurs as depicted in Figure 31. Overvoltage protection is set at 1.1 p.u as per the requirement of the grid coded [1]. PV inverter generation and local load mismatch of up to 15% is at high risk of anti-islanding failure due large non-detection zone. Therefore, a 20% disturbance by Impedance Method is adequate for island detection of a single PV inverter however not adequate when two or more inverters are paralleled even if the disturbance signals are synchronised.

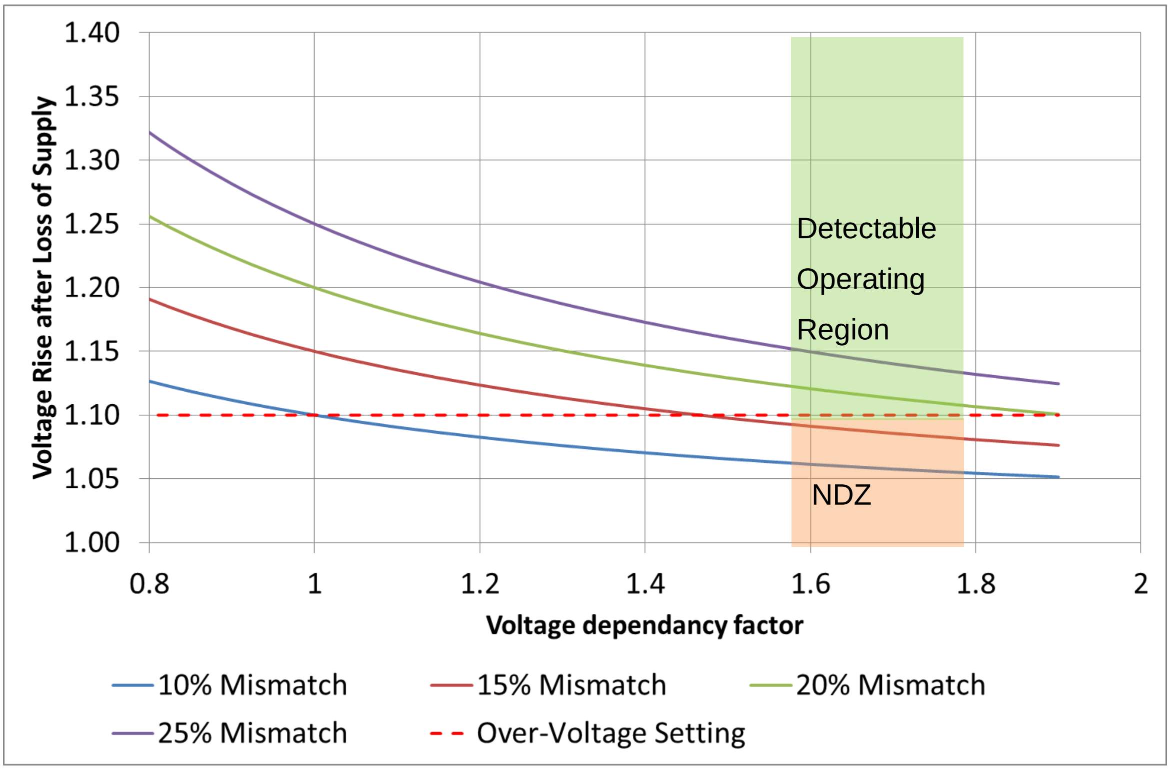

Figure 31: Voltage Rise due to Disconnection of a Grid when PV Inverter Generation is Greater than Load

Figure 32 shows a frequency reduction when PV generation is smaller than load. A Load mismatch up 20% are within non-detection zone and therefore will not be detected by ant-islanding protection. Loss of utility supply will only be detected by under-frequency protection relays if load dependency factor is less than 1.3 and power mismatch is 25% and above.

In case where generation is greater than load, over frequency occurs after loss of a grid and there is a large non-detection zone (NDZ). Over-frequency relay settings of 51.5Hz will not be able to pick up loss of grid as shown in Figure 33.

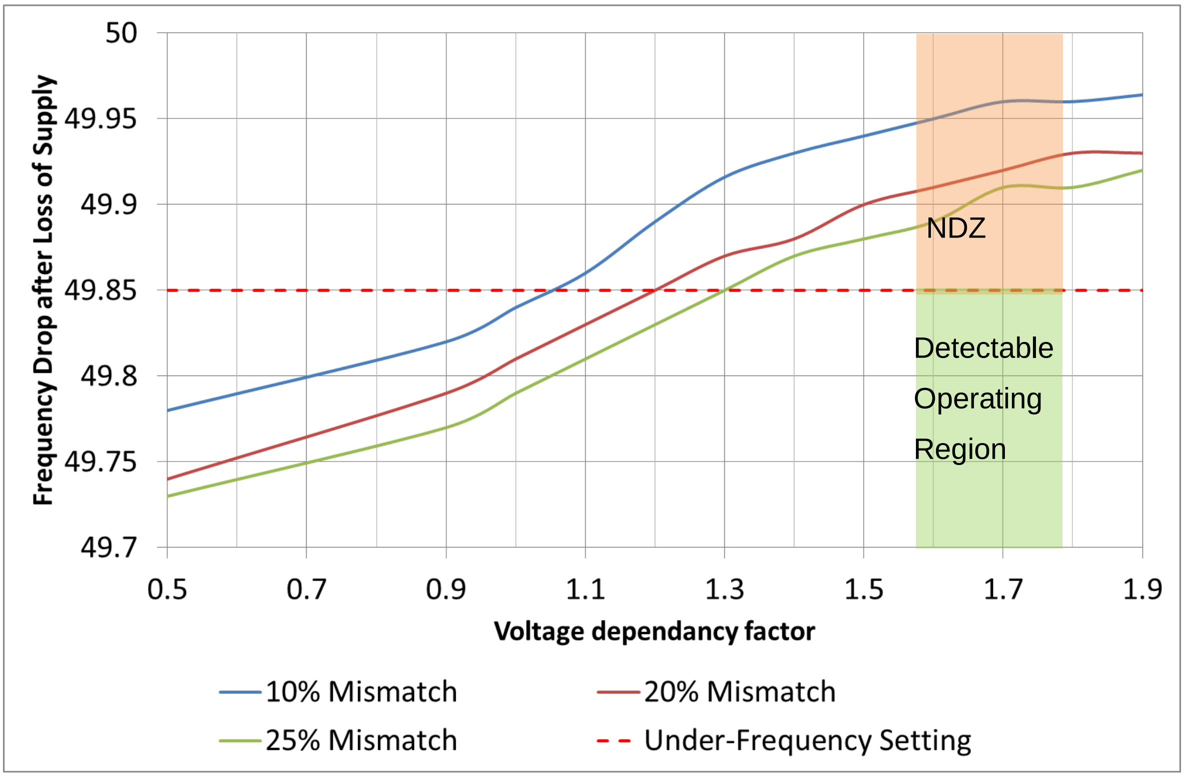

Figure 32: Frequency Drop due to Disconnection of a Grid when PV Inverter Generation is smaller than Load

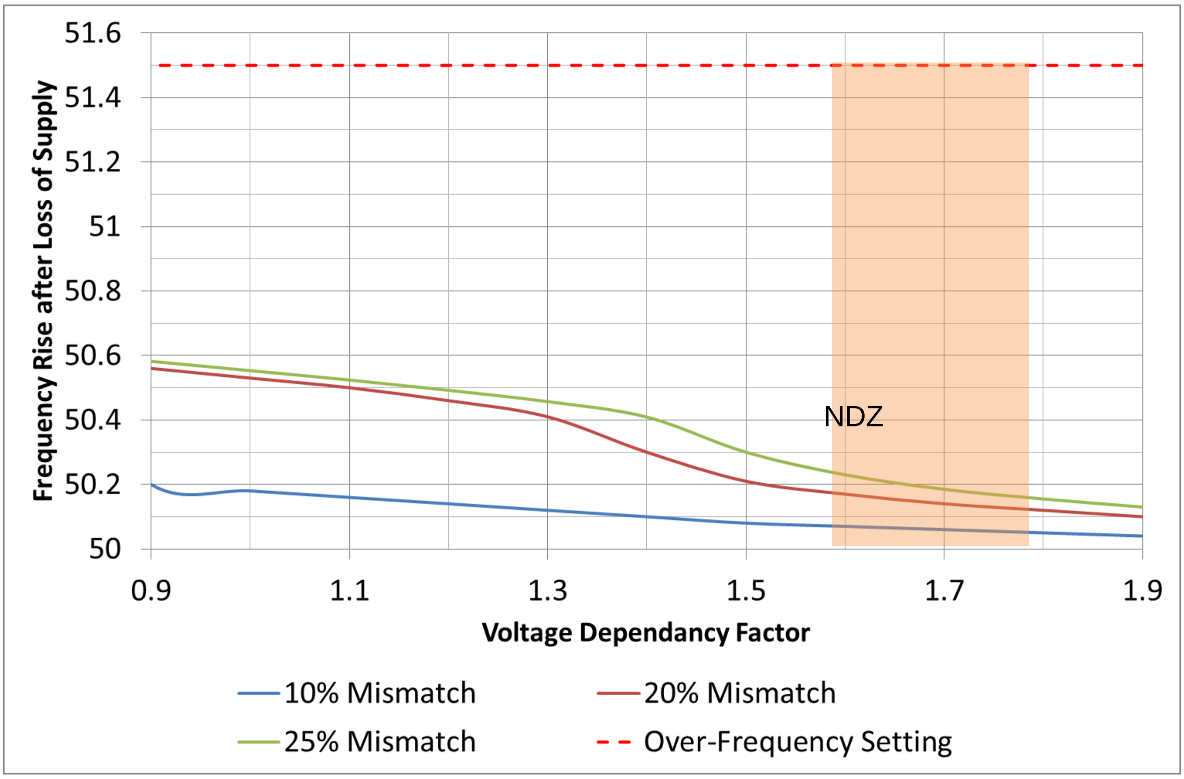

Figure 33: Frequency Rise due to Disconnection of a Grid when PV Inverter Generation is Greater than Load

Phase jump anti-islanding protection is the only effective protection that is able to detect loss of supply in all conditions of load and generation. However, a further investigation is recommended with respect to the protection settings thresholds. No literature was found for protection recommendation of this anti-islanding method, hence NDZ was not established. If load and generation are balanced or equal, there is no frequency or voltage deviation but there is phase jump even at unity power factor. Loads with poor power factor have higher anti-islanding detection threshold.

7.1 Chapter in Perspective

Chapter Seven has demonstrated that Active Method of anti-islanding is more effective when operated in a single mode but less effective when operated in parallel. Therefore it is not advisable to use it in distribution LV network where parallel operation is highly to occur.

The Passive Method of anti-islanding has high Non Detection Zone (NDZ) in residential LV networks. Its performance is not affected when operated in parallel with other inverters, therefore it is recommended for LV Eskom networks.

Chapter 8: Conclusions and Recommendations

8.1 Conclusion

The thesis has demonstrated that there are various anti-islanding strategies and methods that could be used to isolate Embedded Generation from the network. Each strategy has its pros and cons and therefore it needs to be applied where its performance is high. Most countries have adopted a particular strategy that suits their operating and network performance requirements. For example, in the Netherlands they only require schemes that are based on frequency changes whereas other countries like Germany and Austria require methods that are based on sudden impedance changes. Each state in the US has its own unique strategy that addresses their performance, technical and economic issues. Therefore it is critical for South Africa / Eskom to adopt a strategy that is suitable for its operating environment (with respect to performance, technical and economic issues) to ensure safety of plant, staff and public under all operating conditions. In South Africa we might have load mix that is totally different from other international countries such as German, Austria and USA and the load mix has a big influence regarding the suitable method for anti-islanding. South African load is more resistive, most people uses electric heaters, stoves, and geysers, there no other cheap energy alternative available like in other international countries. The study has demonstrated that resistive loads are prone to anti-islanding failure, especially when using passive methods such as U/OVP and U/OFP. Loads that are constant power are perfect to these anti-islanding methods. The more resistive loads the worse for anti-islanding protection. Ideally, for ant-islanding protection requires constant power for better performance which is highly unlikely to occur in the Eskom LV networks.

Load and PV inverter generation mismatch also plays a critical role regarding anti-islanding protection failure. The bigger the power mismatch the smaller the NDZ and better performance of ant-islanding protection. It has been demonstrated that there is a high risk of anti-islanding failure of PV inverters due to high probability of load and generation balance in residential area during the day making it difficult for the grid tied inverters to detect the loss of utility supply, especially when passive methods are used and when more than one active inverter of different design, make and type exist in one zone. Therefore, it is recommended that the utility should use other strategies such as inter-tripping schemes and smart grid technology to enhance isolation of EG in the event of utility supply loss.

Paralleling of passive PV inverter does not affect anti-islanding performance; however paralleling active PV inverters degrade their protection performance. Therefore, it is not recommended to use active PV inverters in parallel. Since, South African Grid Code recommends active method of anti-islanding detection which is only better for single inverter installation, therefore should be reviewed for better network performance and safety of human being. It is anticipated that as the PV penetration levels increases the risk of anti-islanding increases proportionally when active methods are implemented. Therefore, if active methods are used in the network, the operator should ensure that load and generation within a possible island are highly unbalanced in order to rely on U/OVP U/OFP detection method for protection as this is the requirement for all types of inverters. Phase or Voltage Jump Method is one of the best anti-islanding detection methods especially on networks with power factor of less than one. It can be used even on networks with multiple inverters of different type connected in parallel. The phase jump method is highly recommended for South African networks as it is simple and cheap to implement. Although both Frequency Drift / Shift / Bias and Impedance Measurement methods have a very small non-detection zone for a single connected inverter but their performance and effectiveness get reduced as the number of parallel connected units increases and therefore not recommended to be used in Eskom's LV shared networks in order to reduce risk of anti-islanding and improve on human safety.

It should be noted that network operators are required to test the network for dead before performing any working. So, if the network has been isolated upstream and there is still a voltage in the system, may be interpreted as anti-islanding failure and it will require the network operator to identify culprit and manually switch off the supply. One unit failure may cause other unit to continue to generate in a balanced system. Thus, use of smart grid technology will assist for easy identification of the power sources and also assist in isolating such energy sources.

8.2 Recommendations

The following is recommended:

- It is critical to monitor and ensure that the EG cannot supply enough power to the load within an operating zone, for example some utilities employ a two-to-one rule—meaning that the minimum islanded load must be twice as large as the total power that can be generated by EGs per operating zone. This guarantees that the island is not sustainable. This two to one rule can be applied to all Eskom LV networks.
- Safety test before performing any work is highly recommended. If voltage exists on networks that are expected to be dead, the operator is required to identify all energy sources and isolate manually. Note that sustained island can last up to 8 hours.

Presently, there are no operating diagrams and LV database to support this manual isolation of inverters, therefore it is recommended to use of smart-grid technologies for easy identification and isolation of PV inverters when required to do so. The EG should be installed with a smart device in order to monitor and operate the EG circuit remotely.

- In other countries external devices are used for detecting islanding. Normally these devices use the same anti-islanding detection methods as inverter based protection scheme, so it may still present same problems as the inverter based scheme. Therefore such schemes are not recommended.
- Auto-reclosing could harm utility assets and customer assets on LV networks that have high probability of islanding due to out of phase reclosing should the PV inverter anti-islanding fail. Therefore auto-reclosers protection settings should consider existence of PV inverters and auto-reclose should only occur when all inverters are off.
- Feeders known to be part of loading shedding during high generation constraint may no longer address load shedding requirement. Therefore, it is recommended to revise load shedding schedules regularly to avoid shedding feeders with high PV generation when intended for feeders with high load demand. Load shedding should be managed efficiently in order to achieve high system security and performance.
- Voltage regulation might be a problem especially once the utility supply has been restored all EG might connect at the same time and could cause over-voltage in the network if not coordinated efficiently. It is therefore recommended to perform a study to address this issue should it arise.

8.3 Future Work

There are other anti-islanding methods that were not evaluated by this thesis. It is highly recommended to evaluate them as well. The use of communication based methods needs to be evaluated since most literature recommends this technology on radial networks like Eskom LV networks.

It is anticipated that EG will have a big impact on voltage regulation, therefore this require further study.

In LV network there is high probability of net generation especially in zone C, this will require monitoring of voltage and power which could be achieved through smart grid or smart metering. Therefore, effective ways of using smart grid needs to be investigated.

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