Linnæus University
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MSc. Degree Project

Study of Universal Islanding Detection Techniques in Distributed Generation Systems

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Summary

The integration of distributed generation units into the conventional power distribution network is one of the main attributes of the future smart grid electrical power distribution. The high penetration of distributed energy resources (DER) leads to operational challenges, the integration alters the passive nature of the electricity distribution network by injecting a parallel power flow, changing it to an active distribution network.

One of the challenges due to the coupling of distributed generation systems is the undesired islanding condition, it can lead to power electronic equipment damage because parameter changes due to islanding condition expose the inverter to severe working conditions, and the bi-directional current flow and voltage fluctuations can damage customer side equipment. Hence, a static converter-interfaced generation system is required to be equipped with an islanding detection method.

The study investigated the effectiveness of an active inverter resident islanding detection method known as the active frequency drift with positive feedback (AFDPF). It is based on drifting the frequency of the inverter when an islanding situation occurs, by injecting a positive feedback signal. The positive feedback is a function of the frequency changes at the point of common coupling during an islanding fault. The thesis work studied and described the effectiveness of the detection method by comparing the achieved detection time with the standard recommended time for islanding detection time.

Abstract

Energy security, global warming, and climate change have been a major source of global discussions and development. Likewise, the rising cost of electricity for consumers and exponential demand for energy are major factors driving the incremental growth and integration of sustainable forms of energy generation into power the system cycle. Distributed generation resources are majorly integrated into the electricity distribution system at the medium voltage (MV) and low voltage (LV) level of the utility grid system. Unexpected power outages on an electricity distribution network can lead to an islanding situation, in which a distributed generation system continues to supply power to the electricity grid. It is highly recommended by operational standards that, under such conditions, a distributed generation system is disconnected from the grid within a short period to prevent damage to power equipment and ensure personnel safety. The decoupling process requires an islanding detection method (IDM). Such detection methods are implemented in grid-tied power electronic converters (PEC) to detect and prevent islanding conditions.

The thesis investigates and describes an active islanding detection method, the active frequency drift with positive feedback. It also covers the parameter design and the analysis of the non–detection zone. The effectiveness of the method was verified through MATLAB/SIMULINK simulation.

Keywords

Distributed Generation, Islanding, Quality Factor, Resonance Frequency, Low Voltage, Medium Voltage, Electronic Power Converter, Inverter.

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Ochai Ochalla Danladi.

List of Abbreviations

AC – Alternating Current

AFDPF – Accelerated Frequency Shift with Positive Feedback

AFD – Active Frequency Drift.

ADN – Active Distribution Network.

DC – Direct Current.

DER – Distributed Energy Resources.

DG – Distributed Generation.

EPS – Electric Power System

f_o – Resonance frequency.

FRT – Fault Ride Through.

ID – Islanding Detection.

IDM – Islanding Detection Method.

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers.

kV – kilo Volt.

LV – Low Voltage

LVRT – Low Voltage Ride Through.

MV – Medium voltage.

MV – Mega Voltage.

NDZ – Non-Detection Zone.

OFP – Over Frequency Protection

OVP – Over Voltage Protection.

PCC – point of Common Coupling.

PEC – Power Electronic Converter.

PJD – Phase Jump Detection.

PLCC – Power Line Communication.

PLL – Phase Locked Loop.

PV – Photovoltaic.

ΔP – Real Power Mismatch.

ΔQ – Reactive Power Mismatch.

Q_f – Quality Factor.

RLC – Resistance, Inductance, Capacitance.

ROCOF – Rate of Change of Frequency.

ROT – Runoff Time.

SCADA – Supervisory Control

SFS – Sandia Frequency Shift

SMS – Slip Mode Frequency Shift

SVS – Sandia Voltage Shift

THD – Total Harmonic Distortion.

UFP – Under Frequency Protection.

UL – Underwriters Laboratories.

UVP – Under Voltage Protection.

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1 Introduction

The integration of Distributed Energy Resources (DER) into the energy mix is on an exponential rise aiming to reduce the dependence on fossil fuels. Aside from the reduction of greenhouse gases [1], agelong reliance on fossil fuels for energy has proved to be a lopsided form of energy production. Continuous dependence poses a rising and continuous risk to the environment, energy security, and energy cost. Its geographical and political availability goes a long way to show how dependence on fossil fuel completely erodes energy security and reliability. This has imposed a rising cost on energy and the ripple effect leading to some form of global economic crisis. According to Thomas Freidman, ‘‘the country that owns green, that dominates the industry, is going to have the most energy security, national security, competitive companies, healthy population, and most of all global respect’' [2].

DERs, unlike centralized generation from power plants refers to smaller electricity generation units that are usually located on the consumer side of the meter close to the consumers, though not exclusively for some types of DERs. Examples of DERs are rooftop solar system, wind generating units, battery storage systems, biomass generators, fuel cells etc. While the term distributed generation (DG) (also known as embedded or local generation) describes when electricity is produced from renewable sources close to demand or load centres instead of centralised generation points [3], the term DER and DG are overlapping to some extent. The benefit of integrating DER includes but is not limited to the following:

- Reduction in energy cost and improved reliability
- Reduction in overall emission of damaging gases
- Improved energy security

DG systems are designed to operate in a manner that supplies energy only to a local load (grid forming DG system) or by synchronising with an existing utility grid (Grid following DG system) and may do both. They can be interconnected with low voltage (LV<1 kV) and medium voltage (1 kV < MV < 35 kV) electricity grid systems. The interconnectivity of DG systems with the utility grid alters the power flow from unidirectional flow of electricity into a bidirectional power flow system by injecting generation in the distribution system. Under normal operation of an electric power system, it is expected to deliver uninterrupted supply of rated voltage and current. Nonetheless, disturbances or faults in the utility network can create unsuitable occurrences that hinder smooth power transfer, damage power equipment and may be harmful to human. During such unplanned occurrences, it is expected that the DG disconnects from the utility grid to form an island for safety of equipment and personnel. Some of the challenges faced by a grid connected DG system includes power quality and fluctuations, storage, protection, DG placement and islanding [4]. Islanding situations may arise unintentionally; if it is undetected, it exposes personnel and power equipment to dangers associated with high current and voltage levels. The islanding situation impacts the voltage and frequency of the DG and local load negatively, which in turn affects the power quality of the system.

The focus of this thesis work is on islanding detection of a fault in the utility grid resulting in actions in the DG grid. These actions may traditionally include disconnection and grounding of the DG or fault ride through, or different modes of operation as an active distribution network (ADN).

The mode of operation for DGs in the ADN is either the grid connected mode or the islanded mode. In the grid connected mode, power flow to the end user is from both the upstream and local production, while in an islanded mode, the DG is disconnected from the grid and power flowing to the end user comes from only the DGs. The transition between both modes of operation can either be planned or unplanned [5].

1.1 Research Question

The popularity of power electronics-based DG systems interconnecting distribution systems is on the rise and greatly impacts the power system. Power electronics-based grid tied DG system require a secured and dependable protection system that can efficiently detect unintentional islanding and reject disturbances. For effective power transfer and safety, standards and requirements have been developed. Several islanding detection schemes have been designed and integrated to handle unintentional islanding situations. Some of these schemes suffer limitations like large non-detection zone, nuisance tripping, and inability to detect islanding on time and safely. A good number of these limitations are associated with passive methods of islanding detection. Active methods of islanding detection may show significantly better performance. This thesis work will investigate the reliability of the active islanding detection method based on positive feed injection into the inverter system. The impact of a feedback signal in islanding protection will be explored.

The research question to be answered after a comprehensive study of islanding detection methods are:

- Does the active islanding detection method based on positive feedback injection meet the islanding detection standard?
- How can islanding detection be used to meet modern grid codes?

1.2 Scope of the Project

The following conditions discussed below define the scope of the project work. The focus is on the detection of unintentional islanding, and the case study has been performed on a three-phase grid-connected inverter.

- The study and analysis of NDZ of the method of Islanding detection.
- The work is based on a single PEC DG system like the PV Inverter. Multiple strings of inverters were not considered in the thesis work.
- The implemented DG system was operated in a grid parallel mode. The inverter is implemented in MATLAB SIMULINK by utilizing the current control scheme for grid tied inverters. The output of the inverter system was fully matched with the adjoining load.
- Overcurrent and overvoltage protection was not implemented in the study.
- The proposed active islanding detection method is implemented, other methods of active islanding were not evaluated in the thesis work.
- The frequency range of 49 Hz – 51 Hz was used; it is a frequency standard implemented in the Nigeria power grid code [6]. The designed system can also be implemented using other regional frequencies to achieve positive results as well.

1.3 Methodology

To answer the research questions, the following steps were taken.

- Literature study on islanding detection standards. The islanding detection thresholds, time intervals and methods, proposed by international organizations like UL, IEEE and IEC were studied.

- Literature study on active and passive islanding detection methods. The difference between different methods of islanding detection was studied to help determine the most efficient method.
- Implementation of a simulation model. A simulation of an inverter synchronizes with a power grid done in MATLAB SIMULINK is used as a testbed for proposed islanding detection method.
- Simulation of IDM was carried out, to test its effectiveness in islanding situations.

1.4 Thesis Outline

The thesis report is organized in five chapters. The first chapter is an introduction to the topic, giving a general overview of grid tied inverters systems and the need for their protection. Chapter two focuses on a literature review of islanding detection methods. Chapter three focuses on analysing the NDZ of AFDPF from the quality factor and resonance frequency space and mathematical analysis of key parameters required to implement the active method. It also shows the analytical methods of determining Accelerated Frequency Drift with Positive Feedback (AFDPF) parameters. Chapter four is a MATLAB SIMULINK presentation of AFDPF IDM. The results obtained from the implementation are explained here. Chapter five discusses the results of the simulation and includes recommendations for future work to be done.

2 Literature Review

Islanding refers to a situation in which a part of distribution network is disconnected from the grid system, yet the disconnected part is powered by either one or more distributed generation sources. The various islanding detection techniques may not be easily compared since they are mostly applied and designed for specific conditions or systems. For instance, techniques that are operated based on change in terminal voltage are more efficient when applied to synchronous based DG systems, while methods that are based on frequency shift work more effectively with inverter-based DG systems [7].

2.1 Islanding Detection Standards

Unintentional islanding condition cand lead to impairment of electrical equipment and put the life of line workers at risk. To circumvent such occurrences, standards have been drawn up by DG owners and government operators of different countries as safety guidelines for operating a grid forming, feeding, and supporting modes of DG system implementation. Some of the popularly accepted standards are shown in table 2.1 indicating the required voltage, frequency, and detection time thresholds for islanding detection.

Table 2.1: Islanding Detection Standards [8][9][10][11]

Islanding Standard	**Allowable Voltage threshold**	**Allowable Frequency threshold**	**Detection time**	**Description**
UL 1741 [8]	$\mathbf{88\% \leq V_{nom} \leq 110\%}$	$\mathbf{59.3Hz \leq f_{nom} \leq 60.5Hz}$	< 2 sec	Used mainly in active ID, pf limits, voltage regulation, frequency Limitations and multi-DG unit monitoring

IEEE 1547 2018 [9]	$\mathbf{8\% \leq V_{nom} \leq 110\%}$	$\mathbf{59.3Hz \leq f_{nom} \leq 60.5Hz}$	< 2 sec	Microgrid operation, Impact of distribution and transmission, Penetration level, Two-way communication and control, Advance evolution, and testing approaches.
IEC 62116 [10]	$\mathbf{88\% \leq V_{nom} \leq 110\%}$	$\mathbf{f_{nom} - 1.5Hz \leq f_{nom} \leq f_{nom} + 1.5Hz}$	< 2 sec	Hybrid operation of the inverter, Testing limits, Voltage regulation level, Monitoring, and Reconnection specifications
IEEE 929 [11]	$\mathbf{8\% \leq V_{nom} \leq 110\%}$	$\mathbf{59.3Hz \leq f_{nom} \leq 60.5}$	t < 2 sec	Regulation and monitoring small-scale systems.

2.2 Operation Requirements for DG

From the established standards for ID, a DG system is expected to disconnect from the utility grid in case of grid abnormalities and probably continue to energize the adjoining local load. According to the IEEE 1547 – 2018 standard, some of the basic requirements are:

- If the nominal voltage $\mathbf{V_{nom}}$ extends above or below the allowed voltage operating limit of the DG is expected to move into an islanding mode by disconnecting from the utility grid.
- The frequency trip content specifies that if the nominal frequency exceeds the specified limit as indicated **Hz,** the DG should detach from the grid within 0.2 seconds.
- Monitor instantaneous power flow at the PCC of a DG interconnected with the grid for reverse power relaying.

2.3 Non-Detection Zone (NDZ)

The NDZ is a concept used to evaluate the effectiveness of islanding detection methods. It refers to the region with small mismatch percentage where islanding cannot be detected. During islanding conditions (grid disconnection), real and reactive power mismatch occurs at the point of common coupling of the islanded system. The voltage and frequency at the point of common coupling will drift into a region were the load real and reactive power will match that of the inverter. Large imbalance in the system will cause either the UVP/OVP or UFP/OFP relays to trip and interrupt the inverter operation. Insufficient or small imbalance means islanding will not be detected. Hence the real and reactive power mismatch space is used as a criterion to determine the NDZ [12][13]. This mismatch space commonly associated with passive IDMs is rather large. Attempt to reduce passive IDMs NDZ by reducing the thresholds of the protection relays may lead to nuisance tripping.

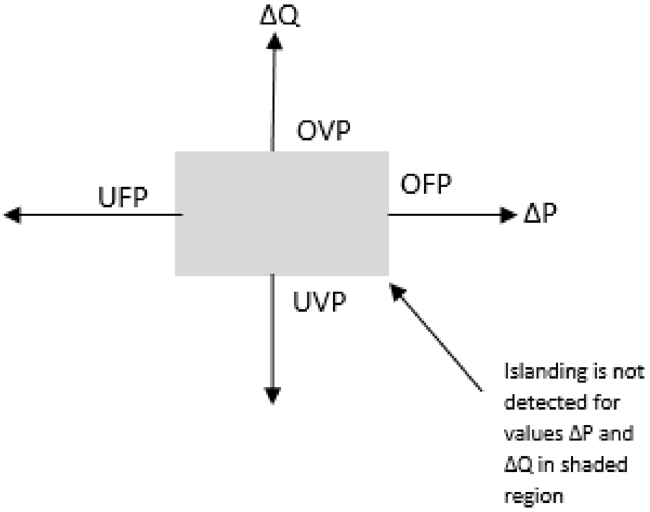

Fig 2.1: NDZ Mapping in the ΔP and ΔQ Mismatch space [14].

Active IDMs exhibit better NDZ schemes [14], however evaluating their NDZ in the ΔP and ΔQ mismatch space is not a sufficient way to rate their effectiveness. The NDZ efficacy of active IDMs is analysed using the RLC parameters of the local load [14]. Some RLC load space parameters used are the normalised capacitance and inductor (C_{norm} vs L) parameter space, quality factor and resonance frequency (Q_f vs f_0) parameter space.

2.4 Islanding Detection Methods

Islanding detection methods are divided into three types, they are communication, active and passive methods. Communication based methods are the most accurate methods, though less popular due to high implementation cost. Passive methods are the easiest to implement and depend on measurable quantities like voltage or frequency measurements at the point of common coupling (PCC). Active methods of islanding detection rely on injecting perturbations (disturbances into the system). These methods of islanding detection consist of several designs depending on what parameters the detection method aims to use.

2.4.1Communication based Islanding Detection Methods

The two major types of communication-based islanding detection are the power line carrier communication (PLCC) and Supervisory Control and Data Acquisition (SCADA).

2.4.1.1 Power Line Carrier Communication (PLCC) Islanding Detection.

PLCC has been proposed to counter some of the challenges encountered with inverter-based islanding prevention methods [15]. PLCC systems operate by sending a low energy communication signal over the power line. The signal sent over the power line is used to perform a continuity test between a receiver device located at the customer end of the power line. The inverter remains in a grid connected mode if the PLCC signal remains. Once the PLCC signal disappears, it indicates a power line or grid failure, and the inverter and load are isolated from the PCC. PLCC methods are currently implemented in load shedding operations, signals are sent from the utility to non – critical loads during high load conditions in highly populated and industrialised areas. The PLCC islanding detection technique does not have an NDZ, hence its effectiveness in islanding prevention. It has zero effect on power quality of the inverter output power. it can also be implemented in situations with multiple DG systems [15]. A major setback for PLCC IDM is the high cost of implementation of PLCC transmitters across the distribution network of inverters. It is mostly restricted to high – density distribution areas. Also in islanded mode, motors that are subjected to external vibrations draw harmonic currents that may interfere with the PLCC carrier, thus the PLCC device may fail to disconnect the inverter [16].

2.4.1.2 Supervisory Control and Data Acquisition (SCADA)

Well organised inclusion of PV inverters within SCADA systems can aid islanding detection due to the extensive use of communication in power utility systems for monitoring, control, and rapid response to emergencies. Utility systems involve a lot of instrumentation controls for monitoring high voltage transmissions and controllable switching devices at all levels of the utility network. Using SCADA for islanding detection involves installing a voltage sensing device alongside a PV inverter in the downstream section of the utility system. If the voltage sensors detect a voltage when the utility is disconnected from part of the system, a recloser can be installed in coordination with the inverter to prevent an out-of-phase reclosure. If the system is properly installed and the required communication links are available, it should be able to eliminate islanding. This method has shortcomings when implemented in situations with multiple inverters. Separate instrumentation and communication links are required for each inverter, which makes it cumbersome and expensive. If it is implemented properly, NDZ does not exist [17].

2.5 Passive Islanding Detection Methods

To detect islanding, passive islanding detection techniques measure system parameters such as voltage, frequency, and total harmonic distortion etc. Grid connected PV inverters are required to have protection schemes such as over voltage and under voltage protection, and over frequency and under frequency protection. The protection methods of the PV inverter prevent power supply to the grid in the event of voltage amplitude and frequency at the PCC drifting outside the required limit. The characteristics of the system during grid fault or disconnection depends on real and reactive power flowing the moment the breaker opens to form an island. If the voltage at the PCC changes, OVP/UVP detects the changes and disconnects from the grid. The load voltage will shift in phase causing the frequency of the inverter output current and the frequency at the PCC to change until it reaches the load resonant frequency. Changes in the frequency are tracked by the OFP/UFP protection system in the inverter. The OVP /UVP and OFP/UFP serve as backup protection for systems implementing other forms of islanding detection that tend to produce abnormal amplitude and frequency. It is also a cost-effective IDM and ensures protection of loads and equipment. A large NDZ is a major weakness in this method of detection [18].

2.5.1 Voltage Phase Jump Detection (PJD)

This method of detection monitors the phase difference between inverter terminal voltage at the PCC and output current for a sudden jump when islanding occurs. During the switching into island mode, the phase angle of V_{pcc} and its output current synchronise with the phase angle of the local load, the shift results in a phase change at the PCC. It is quite difficult to implement because choosing a threshold for reliable islanding detection that may not result in nuisance tripping is difficult. It is necessary for the inverter to operate at unity power factor for the NDZ of this method to work; NDZ changes if the inverter is not operated at a unity power factor [17].

2.5.2 Rate of Change of Frequency (ROCOF)

High frequency switching, DC link voltage ripples and dead time effect makes a grid tied inverter to produce harmonics. These harmonics cause distortions in the voltage waveform at the PCC that are not noticeable in grid – connected systems during islanding conditions. Distortions in the voltage waveform at the PCC causes some frequency variations that leads to rate of change of frequency (ROCOF). Islanding can also be detected by employing the ROCOF waveform [20].

2.5.3 Harmonic Detection

In this method, the inverter in the DG is designed to keep track of the total harmonic distortion (THD) at the PCC and shuts down if the THD exceeds a set threshold. In grid connected mode, the distortion is low (THD 0) across load terminals, hence the current fed to the load is an undistorted sinusoidal current. Also, in grid connected mode the harmonic currents produced by the inverter flows into the low – impedance grid. In a typical situation, the THD of the V_{pcc} is below detection point or threshold. When islanding occurs, the inverter causes the V_{pcc} to increase by producing current harmonics in its AC output. In off – grid mode, the harmonic current from the inverter feeds the load which has a higher impedance than the grid. The interaction between harmonic current and large load impedance generates larger harmonics at the PCC [21]. The variation in the voltage harmonics can be detected by the inverter and further discontinue operation.

2.6 Active Islanding Detection Method

In general, active islanding detection techniques contain active circuits that measure frequency, voltage, and impedance when a grid fault is detected. This is achieved by injecting small signals into the system and trying to detect signal changes when there is an islanding condition. The distortion is injected into the output current of the DG system by changing its amplitude, phase, or frequency [22]. In grid connected mode the injected disturbance is absorbed by the utility grid, making it less significant. When the grid is disconnected (islanding occurrence), the distortions are meant to push the operating point of the island to a threshold point that triggers the protection devices of the system.

2.6.1 Impedance Measurement

Impedance measurement is implemented by measuring the equivalent impedance of the circuit fed by the inverter. Three parameters may be measured, the current amplitude, $\boldsymbol{I_{pv\text{-}inv}}$, the frequency $\boldsymbol{\omega_{pv}}$ and the phase, $\boldsymbol{\o_{pv}}$. A variation is continuously imposed on one of these parameters, often the amplitude [23]. In the grid connected mode, voltage disturbances or perturbations from the current amplitude depend on the grid resistance and power. If the grid is disconnected, the variation will drive a detectable change at the PCC that can be used to prevent islanding. This method has in theory an extremely small NDZ when implemented for a single inverter system. A major challenge of this method is its ineffectiveness in situations with multiple inverters; multiple inverters lead to small variation of the parameters.

2.6.2 Impedance Measurement at Specific Frequency

The impedance measurement at specific frequency is a different method of harmonic detection method viewed as an active method rather than a passive method of detection. This is because it is implemented by injecting current harmonics at a specific frequency into the PCC via the inverter. In grid connected mode, if the grid impedance is lower than the load impedance at the specified harmonic frequency, the harmonic current flows into the grid. When the grid is disconnected, the harmonic current flows into the load. If the load is linear (RLC load), it produces a harmonic voltage that can be used for islanding detection [23][24].

2.6.3 Slip Mode Frequency Shift (SMS)

The SMS method uses positive feedback to perturb the PV inverter when the grid is disconnected. It is achieved by applying positive feedback to the phase of the PCC voltage to shift the phase. The current – voltage phase angle of the inverter is designed to be a function of the frequency of the PCC voltage. The implementation of SMS ensures that the phase of the inverter increases faster than the phase of the linear load (RLC load) with a unity power factor in the region near the grid frequency, making the line frequency an unstable operating point for the inverter [23][24] The system drifts away from the designed frequency which can be used for islanding detection. It requires a well-designed phase locked loop (PLL) to become unstable in off – grid mode.

2.6.4 Active Frequency Drift (AFD).

The output current waveform is modified with the Active Frequency Drift (AFD) islanding detection method by adding a dead-time part "drift" at the end of each half cycle. The ratio $\frac{2t_z}{T_{vutil}}$ is known as chopping factor. Under normal operation, this chopping factor remains constant in grid-connected mode. During islanded operation, however, the chopping factor constantly increases as the frequency tries to match the load resonance frequency. When the chopping factor exceeds a certain threshold, islanding occurs, and the DG is disconnected. When compared to SMS, this approach produces wider NDZ, according to testing. It also introduces a distortion to the DG output in detecting islanding, which may create transient difficulties and power quality concerns [17][23].

2.6.5 Accelerated Frequency Drift with Positive Feedback (AFDPF)

Also known as sandia frequency shift (SFS), this method is an improved version of AFD. It uses positive feedback to moderately alter the phase angle of the inverter output current by adding dead time to the current waveform. The deadtime in the wave form drifts the frequency of the current during grid fault. the chopping frequency of factor indicated in (1) is a calculate as due to error in the grid frequency. where Cf_o is the initial chopping factor in grid-connected mode when there is no frequency deviation, K is the positive feedback gain, f is the measured frequency, and f_o is the nominal frequency or grid frequency.

$$C_f = cf_o + K(f_m - f_g) \tag{2-1}$$

The frequency change in grid-connected mode is relatively minimal, and the chopping frequency is essentially zero, making the chopping factor a small value. The chopping factor will thus rise or decrease until the OFP/UFP limits is reached to trip the DG. This technique significantly improves the standard AFD and has the benefit of having a smaller NDZ. However, because of the positive feedback, it also results in decreased power quality. This technique is intended to be used with inverter-based DG systems [23][25].

2.6.6 Sandia Voltage Shift (SVS)

The Sandia Voltage Shift (SVS), which applies positive feedback to the voltage amplitude, is implemented in conjunction with SFS. In SVS, the power output of the inverter is decreased to decrease the voltage. This power decrease in grid-connected mode has a negligible effect on the output voltage. However, due to the loss of power during islanding, the voltage decreases. the under – voltage relay trips and disconnects the DG unit from the system as the positive feedback continues to reduce the voltage [23][26]. When combined with SFS, the SVS method is simple to apply and can easily detect islanding. Due to the positive feedback, the disadvantages are the decrease in DG efficiency and power quality. Techniques for active islanding detection have the benefits of having a small NDZ and very accurate results. These benefits are achieved as a trade-off of power quality, decreased DG unit efficiency, and prolonged detection times.

2.7 Hybrid Islanding Detection

Hybrid islanding detection is a detection method that combines two existing method of islanding detection in a single DG. The goal is to overcome the detection limitations associated with both combined methods to achieve faster and more effective islanding detection. It is mostly a combination of the active and passive methods of islanding detection [23][27].

2.8 Fault Ride Through of PV Grid Connected Inverter

The increasing capacity of PV integration into the energy mix suggests the need for it to contribute towards stability, operability, reliability, and quality. It has become necessary for PV power plants to act as conventional power plants to manage grid faults. Earlier grid standards required the PV inverter systems that are grid-connected to disconnect from the power grid during fault. Such instant interruptions could lead to further stability problems [28]. To lessen the gravity of this challenge, PV grid-tied inverter systems must meet low voltage ride-through (LVRT) or fault ride-through (FRT) capabilities. This also implies that inverter control designs should incorporate FRT controls [28]. FRT capabilities enables the PV grid tied inverters to provide dynamic voltage support (DVS) by injecting reactive power.

An FRT capable PV grid tied inverter requires a control system that can stand voltage disturbances and enable it to supply reactive current to the power grid for voltage support and to achieve FRT during faults. This can be accomplished by addressing two crucial situations via the inverter control system. Once a fault occurs the inverter control should be able to manage over current issue on the AC side of the inverter and over voltage on the DC side, which arises due to the distinction between incoming PV energy and the energy transported to the grid [29]. The second issue that needs to be addressed by the PV inverter control system is the injection of reactive current into the power grid for voltage support during voltage sag [30].

2.8.1 Grid Code Fault Ride Through Requirements

A recommend practice by most grid codes is quick disconnection of the PV inverter from the grid in case of a grid fault [31]. This form of swift disconnection affects power grid stability, particularly in large scale PV power plant integration. To avert the further instability and stabilize the grid, New FRT or LVRT standards requires the PV inverter to remain connected to the power grid during certain percentage drop in grid voltage for a specific period.

For instance, the FRT grid code requirement of the German grid code requires the PV grid tied inverter to stay connected to the power grid to perform a zero ride through operation if the voltage at the PCC drops to zero for a period of 0.15 seconds and are expected to disconnect if the voltage drop remains after 1.5s. [32] In addition to staying connected during fault period, the PV inverter is required to participate in grid support by injecting reactive current. The injected reactive current depends on the level of PCC voltage decrease, the normal operation of the grid when the amplitude ratio of grid voltage to its nominal value is between 0.9 p.u – 1.1 p.u. A critical point where the amplitude ratio of the grid voltage to its nominal value is below 0.5 p.u, the DG system injects a reactive current equal to the nominal current. It is expected that when fault is restored, normal operation of the PV inverter is resumed, the power factor returns to unity and the supply of reactive current is discontinued.

Low Voltage Ride Through (LVRT) is the term used to describe the ability of solar inverters to operate during voltage sags. If the circumstance or period under which the fault is to be restored is exceeded and the fault persist the inverter disconnects from the grid and the islanding detection method swings into action to prevent the islanding situation by stopping the PV inverter continuous power transfer to the grid [33].

3 Methodology

3.1 Introduction

Accelerated frequency drift with positive feedback (AFDPF) is implemented in this study. This method of detection aims to drift the frequency of the inverter current through a positive feedback scheme. In the event of islanding, the frequency shift method detects changes in frequency and starts to shift inverter current frequency in the same direction (either beyond the upper or lower limit of the relay trip limits). It is a reliable method of islanding detection and does not inject periodic disturbances into the grid [17].

The system under study consists of a three-phase power grid utility source, the DG system is a 20 kW DC voltage source converter (inverter). The interface controller for the DG is a constant current control handling both voltage and current. The control scheme is based on the ***dq*** synchronous reference frame. The DG is connected to a 10-kW load at the PCC. Both the load and the DG are connected to the grid. Figure 3.1 is a single line diagram representation of the system considered for islanding detection study that was implemented in three - phase.

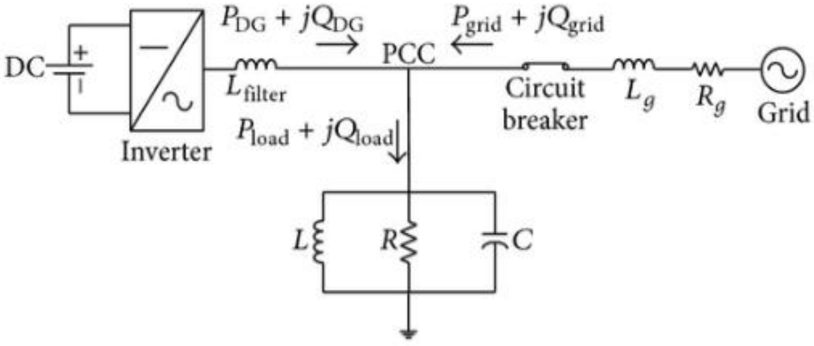

Figure 3.1 System under study [22].

The SFS method improves the flaws associated with AFD IDM, the strategy is to improve AFD with zero current segment t_z (a method of implementing AFD) illustrated in figure two. To improve the AFD zero current segment, the SFS method implements positive feedback to increase the chopping frequency (fraction). It is the ratio of the dead time t_z to one half of the period of the V_{pcc} waveform, and is expressed as:

$$cf = \frac{2t_z}{T_v} \qquad \textbf{(3-1)}$$

The increase deviates the frequency from its nominal value. The deviation is due to the change in the frequency of the PCC voltage, and directly proportional to it. It is expressed in equation 3-2:

$$cf = cf_0 + F(\Delta f) = cf_0 + K(f - f_g) \qquad \textbf{(3-2)}$$

cf_0 is the initial chopping factor when there is no frequency error, while K is the accelerating gain factor.

The effect of the zero current period causes the voltage waveform at the PCC to go to zero faster than it would have done under normal sinusoidal operation. It also leads to quick rising zero crossing of the PCC voltage waveform. These changes give rise to a phase shift between the inverter output current and PCC voltage. Hence, the inverter angle of SFS IDM due to the phase shift is expressed as:

$$\theta_{sfs} = \frac{2\pi f t_z}{2} = \pi f t_z = \frac{\pi cf(f)}{2} \qquad \textbf{(3-3)}$$

3.2 Non - Detection Zones of AFDPF Islanding Detection Schemes

Non detection zone (NDZ) is a concept used for analysing the effectiveness of an islanding detection method. It refers to the region or limits in which an islanding detection method fails to detect islanding. NDZ of active islanding detection methods cannot be analysed in the ΔP and ΔQ parameter space used in passive IDM analysis. This is because different values of RLC load yielding different result for islanding detection will be analysed at the same point [34]. To overcome this, the capability of active frequency drifting IDMs is examined for different load parameter combination, and the NDZ is defined through calculation as an expression of the control parameters. The basis of the load parameter criterion is known as the phase shift criteria, which states that in the steady state operation of a grid connected DG system, the islanding frequency of such system is such that the load angle is in phase with the inverter angle [35]. Hence, to obtain the NDZ of frequency-shifting IDMs, the expressions for the inverter phase angle and load parameters are required. The NDZ of SFS islanding detection method in this study is based on the quality Q_f factor and resonant frequency f_o (Q_f x f_o) of the RLC load. The inverter phase angle and load parameters are defined in the following sections.

3.3 RLC Load Model

To evaluate an IDM, the load is generally modelled as an RLC load because it presents some difficulties in detection, particularly for loads with high-quality factor. RLC loads allow efficient testing of different islanding configurations. Usually, nonlinear loads such as harmonic or constant power loads do not present difficulties in islanding detection [26]. To further understand the principles of IDM, the load phase angle and impedance are derived in the following sections.

3.3.1 Load Quality Factor.

If the match of the real power generation to load is in the range of fifty percent, and the power factor is greater than 0.95, it is recommended that a non-islanding inverter disconnects from the utility grid within a period of two seconds at any time the line quality factor is less than or greater than 2.5 [11]. The quality factor is defined as two pi times the ratio of maximum energy stored to the energy loss per cycle at a given frequency.

$$\boldsymbol{Q_f = 2\pi \frac{maximum\ Energy\ Stored}{total\ energy\ loss}} \qquad \textbf{(3-4)}$$

The quality factor is inversely proportional to the power factor, hence loads with a quality factor of 0 – 2.5 are suitable for all distribution and load layouts [11]. The quality factor of an RLC load can be expressed in terms of the load circuit parameters and it is given as:

$$\boldsymbol{Q_f = \omega_0 RC = \frac{R}{\omega_0 L} = R\sqrt{\frac{C}{L}}} \qquad \textbf{(3-5)}$$

The quality factor of the load is dependent on the frequency at which it is tested (the resonant frequency of the circuit). For the voltage across the load to be synchronized with the inverter, the frequency of the inverter is considered equal to the resonant frequency of the load, and in that case the magnitude of the voltage relies on the load resistance.

3.3.2 Phase Angle Characteristics of RLC Load

The magnitude of the admittance Y of the RLC circuit is given by:

$$|Y| = \sqrt{\boldsymbol{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{j\omega L}\right)^2}} \qquad \textbf{3-6)}$$

The phase angle of the load is calculated from equation 3-6 as:

$$\boldsymbol{\theta_{LD} = tan^{-1}\left[R\left(\omega C - \frac{1}{\omega L}\right)\right]} \qquad \textbf{(3-7)}$$

The phase of an RLC load for any random frequency in terms of quality factor and the load resonance frequency is given by:

$$\boldsymbol{\theta_{LD} = \tan^{-1}\left[Q_f\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right]} \qquad \textbf{(3-8)}$$

Equation 3-8 represents the phase angle in degrees by which the current leads the voltage.

The characteristic curve of the load phase angle and frequency for different quality factors and load resonant frequency is shown in figure 3.2. The curve indicates that a higher quality factor results in a higher deviation of the phase angle around the resonance frequency. Moreover, figure 3.3 is a characteristic plot of the phase angle and frequency for a fixed quality factor of 2.5 and different resonant frequencies, it shows that the phase angle is zero at the resonant frequency, where the load angle and the frequency intersect. At the resonant frequency, the RLC circuit is purely resistive. In addition, a load with resonant frequency lower than the grid frequency ($f_0 < f_g$**)** is an indication of large capacitive circuit impedance, and for ($f_0 > f_g$), there is a larger inductive impedance.

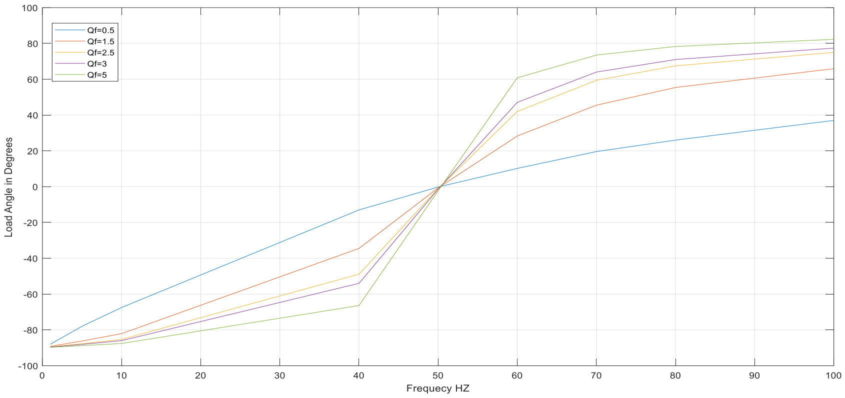

Figure 3.2: Variation of RLC load angle and frequency due to fixed resonance frequency and different quality factor.

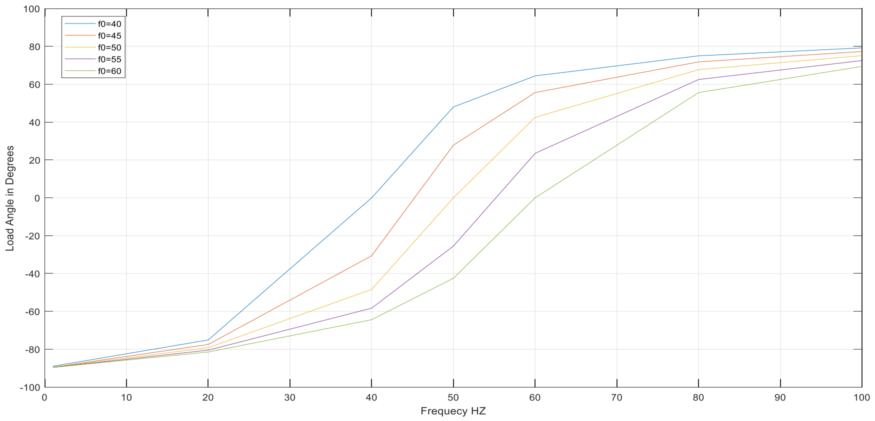

Figure 3.3: Variation of RLC load angle and frequency due to fixed Quality factor and different resonant frequency.

3.4 Non-Detection Zone (NDZ) of Drifting IDM

The working principles of active IDMs are typically framed for the worst-case situations of passive OVP/UVP and OFP/UFP, which implies that for a grid rated voltage and frequency, the power imbalance or mismatch is zero as the voltage magnitude and frequency remain constant after disconnection from the grid. A resourceful way to achieve active IDM is trying to drift the frequency and voltage at the PCC to a region outside the operating limits of OVP/UVP and OFP/UFP systems [11]. IDMs that rely on change in the frequency at the PCC to detect islanding are examined using the phase criteria.

3.5 Non - Detection Zone of AFDPF in the Quality Factor vs Resonance Frequency Space

The non–detection zone of the proposed islanding scheme is analysed based the quality factor versus resonant frequency of the RLC load parameter space. It is derived using phase criteria stated in equations 3-9.

$$\boldsymbol{\theta_{LD} = \theta_{inv}} \tag{3-9}$$

The inverter phase angle of an AFDPF islanding detection method is given as:

$$\boldsymbol{\theta_{inv} = \frac{\pi}{2}\left(C_{fo} + K\left(f - f_g\right)\right)} \quad \textbf{(3-10)}$$

Based on the phase criteria, substituting 3-9 with 3-8 and 3-10, gives:

$$\boldsymbol{arctan\left[Q_f\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right] = \frac{\pi}{2}\left(C_{fo} + K\left(f - f_g\right)\right)} \quad \textbf{(3-11)}$$

Solving equation 3-11 and equating to zero results in the quadratic expression of equation 3-12:

$$\boldsymbol{f_0^2 - \frac{tan\,\theta_{inv} f}{Q_f} f_0 - f^2 = 0} \quad \textbf{(3-12)}$$

Solving equation 3-12 in terms of the resonance frequency gives:

$$\boldsymbol{f_0 = \frac{f}{2Q_f}\left(-\tan\theta_{inv}\,(f) + \sqrt{tan^2\theta_{inv} + 4Q_f^2}\right)} \quad \textbf{(3-13)}$$

Expression 3-13 gives the resonance frequency that will lead to the to the islanding operation. Replacing the frequency $\boldsymbol{f}$ by the islanding frequency $\boldsymbol{f_{isl}}$ then gives:

$$\boldsymbol{f_0 = \frac{f_{isl}}{2Q_f}\left(-\tan\theta_{inv}\,(f_{isl}) + \sqrt{tan^2\theta_{inv}(f_{isl}) + 4Q_f^2}\right)} \quad \textbf{(3-14)}$$

The NDZ boundary lies between the upper and lower limits of the islanding frequency. The islanding frequency is defined by the upper and lower limits of the UFP/OFP trip limits ($\boldsymbol{f_{max}}$ and $\boldsymbol{f_{min}}$). The boundary limits for AFDPF IDM in the $\boldsymbol{Q_f}$ x $\boldsymbol{f_0}$ load parameter space is given by:

$$\boldsymbol{f_{0max} = \frac{f_{max}}{2Q_f}\left(-\tan\theta_{inv}\,(f_{max}) + \sqrt{tan^2\theta_{inv}(f_{max}) + 4Q_f^2}\right)} \quad \textbf{(3-15A)}$$

$$\boldsymbol{f_{0min} = \frac{f_{min}}{2Q_f}\left(-\tan\theta_{inv}\,(f_{min}) + \sqrt{tan^2\theta_{inv}(f_{min}) + 4Q_f^2}\right)} \quad \textbf{(3-15B)}$$

$$\boldsymbol{f_{0max} = f_{0min} = \frac{f_g}{2Q_f}\left(-\tan\theta_{inv}\,\left(f_g\right) + \sqrt{tan^2\theta_{inv}\left(f_g\right) + 4Q_f^2}\right)} \quad \textbf{(3-15C)}$$

3.6 Design of Shift Constant, K

For the system to operate a steady state island, the inverter phase angle is equal to the load phase angle as stated in equation 3-9.

$$\boldsymbol{\theta_{LD} = \theta_{inv}}$$

The equilibrium point defined by equation 3-9 must be unstable to detect islanding. The instability criterion is achieved by making the inverter phase angle and its related parameters greater than the load phase angle and its related parameters to ensure effective detection [36]. The instability criterion is expressed as:

$$\boldsymbol{\varphi_{inv}\left(C_{fo}, K, f\right) > \varphi_{LD}\left(f_0, f, Q_f\right)} \tag{3-16}$$

Which implies this:

$$\boldsymbol{\frac{\pi}{2}\left(C_{fo} + K\left(f - f_g\right)\right) > -\tan^{-1}\left[Q_f\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right]}$$

Solving the inequality of equation 3-16 in terms of K:

$$\boldsymbol{k > -\frac{C_{fo} - \frac{2}{\pi}\tan^{-1}\left[Q_f\left(\frac{f^2 - {f_{res}}^2}{f_{res} \times f}\right)\right]}{\left(f - f_g\right)}} \tag{3-17}$$

Evaluating equation 3-17 gives the base value of K, 20% of the calculated value of K is to be added to K do drift the frequency above the upper or lower frequency protection limits (islanding frequency). The highest value of the initial chopping fraction is ±0.046 [37]. Choosing the value of the chopping fraction used in tuning K depends on the resonant frequency. If it is greater than the grid frequency, the initial chopping fraction for tuning the shift constant will be positive (+0.046), else the negative value (-0.046) is used for tuning.

3.7 Frequency Relay

A frequency relay operates when the system frequency exceeds a predetermined value. According to the American National Standard Institute (ANSI) and IEEE a frequency relay is usually assigned a device number 81 [39]. A frequency relay can either be under frequency relay (81U or 81L) or over frequency relay (81O/81H). The relay implemented in the design is an over frequency relay, it is actuated by rise in electrical frequency and for this design if the limits of the inverter current exceed 51 Hz the relay is actuated, and a trip command is sent to the circuit breaker to open and stop the inverter from supplying power to grid. The frequency relay implemented is originally developed and contributed to MATLAB. [38].

4 Simulation and Results

4.1 Design and Simulation

This chapter aims to validate the theoretical analysis and equations that describe the NDZ in the Q_f x f_o load parameter space and islanding detection when implementing the AFDPF islanding detection method. The simulation has been performed using MATLAB Simulink software. The simulation schematic is described in section 4.2, the results are presented in section 4.3 and the comparison with the derived equations are further analysed in this section. Finally, section 4.4 gives the conclusion of the results.

4.2 Simulation Schematics

The figure described in fig. 2-1 was modelled using the MATLAB Simulink software as shown in figure 3.2. it comprises of a 3-phase voltage source inverter that represents the PV array and converter. The filter circuit is an LCL filter, the voltage source inverter feeds a three phase RLC load with a capacity of 10kW at the point of common coupling (PCC). The 3-phase breaker connecting the VSC to the grid opens at a pre-set time to simulate a fault on the grid. The control system of the DC – AC converter is current controlled using a PI regulator in the synchronous reference frame. By locking the reference frame to the utility supply, the d-axis control represents the active power and q-axis control represents the reactive power of the inverter. To synchronise to the grid, a phase locked loop (PLL) is implemented. To detect islanding, the SFS islanding detection method is implemented.

4.2.1 DC – AC Converter and LCL Parameters

The values of the parameters DC – AC and LCL filter implemented in the MATLAB SIMULINK simulation are shown in the table below:

Table 4.1: Load and inverter parameters in Simulation.

Load and System Parameters	
Grid Frequency	50Hz
Grid Voltage (rms)	400V
R	48 Ohms
L	0.0204 H
C	497.4×10^{-6}
Load Quality Factor	2.5
PV System power	20kW
Resonance Frequency	50 Hz

the synchronisation of the inverter to the grid is shown in figure 4.1, it is a wave form of the inverter current output synchronised with the grid voltage. It is a recommended standard for grid connected inverters to operate effectively with grid.

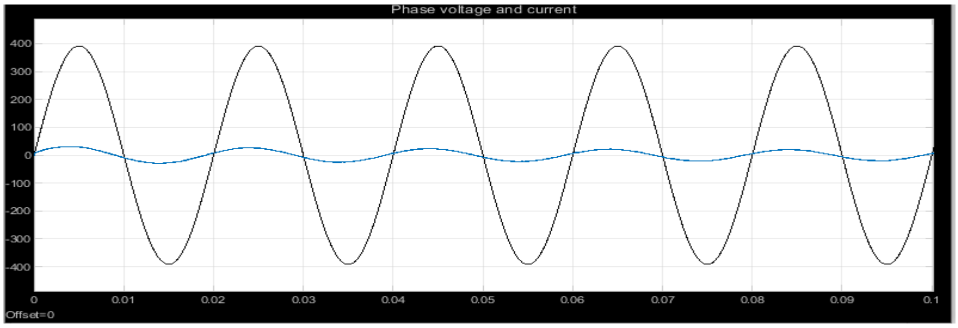

Figure 4.1 Inverter current synchronised with grid voltage.

4.3 SFS Islanding Implementation

The AFDPF (SFS) detection scheme makes use of the inverter terminal voltage frequency as a positive feedback signal. The voltage frequency is measured from the 3-phase PLL. The output of the SFS block and the inverter current and its reference value processed by the current controller are transformed into three phase voltages used to control the inverter. The SFS block defines the inverter phase angle as a function of island or measured frequency, grid frequency before islanding occurs and the AFDPF parameters **C**$_{fo}$ and K. It is shown in figure 4.2 and its output is as illustrated in Figure 4.4.

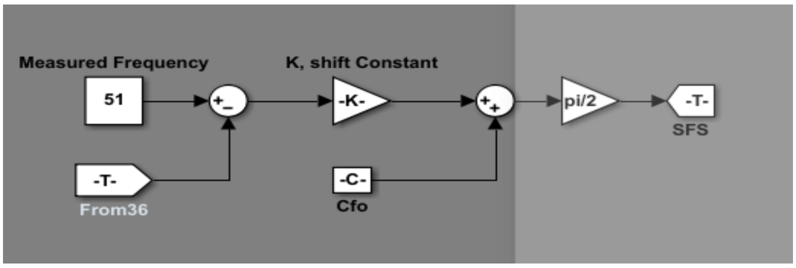

Figure 4.2 AFPDF phase angle implementation.

The trip limits used for the frequency protection relays of the design are 2% above and below the grid frequency of 50Hz. They are also used as the islanding upper frequency limit and islanding lower frequency limit respectively.

Table 4.2 Frequency Protection Relay Trip Limits.

Upper Relay Trip Limit	(50x2%) + 50	51 Hz
Lower Trip Limit	50 – (50x2%)	49 Hz

4.4 Frequency Shift Constant, K

The shift constant K was tuned using equation 3-17 for loads of different quality factor and the accompanying load resonance frequency, the result obtained is shown in figure 4.3. the middle blue line is a point where the initial chopping fraction is zero, a more stab frequency shift can be achieved by implementing lower values of K as shown by the orange and yellow lines.

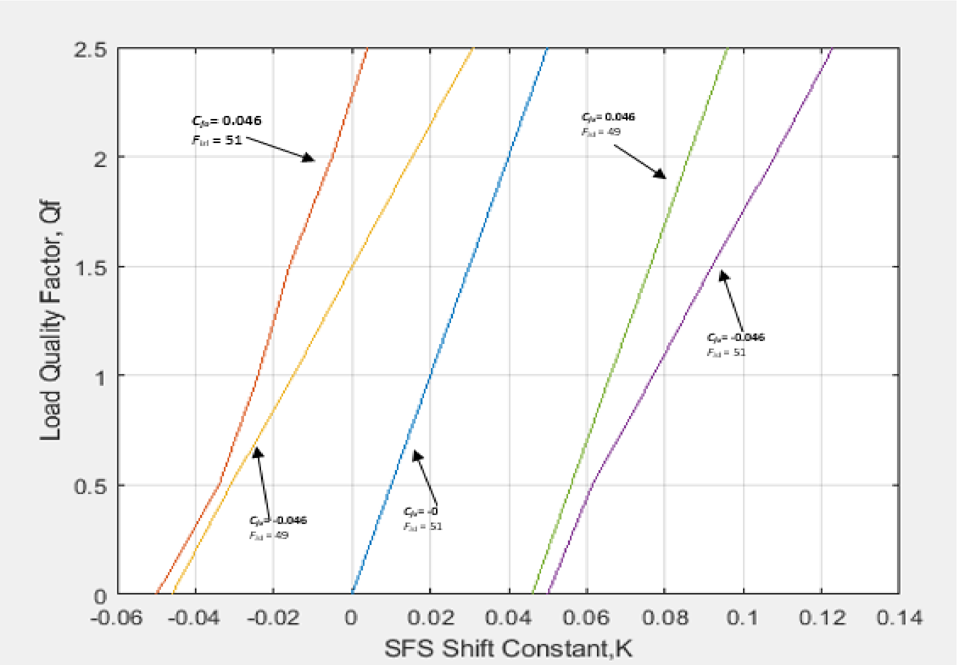

Fig.4.3 Plot of Quality Factor and Shift Constant K.

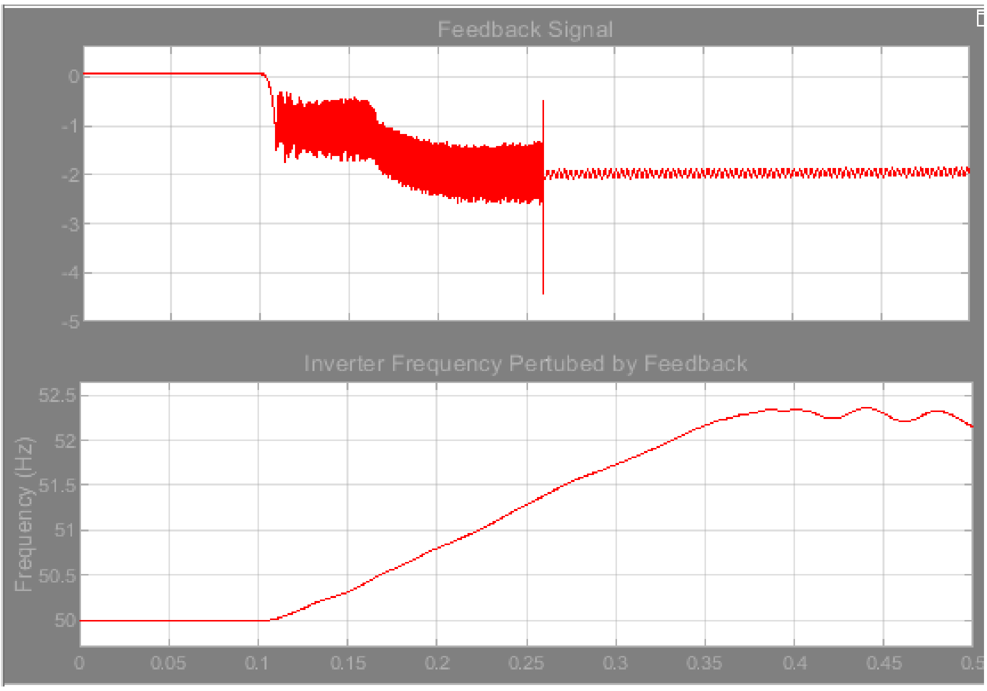

Fig 4.4 Impact of Positive Feed Back Signal on System Frequency.

Once grid fault or outage occurs at 0.1s, an islanding situation is formed, as seen in figure 4.4, the feedback signal starts perturbing the inverter current towards the upper limit of the protection limit.

4.5 Model Derivation in MATLAB SIMULINK

In the AFDPF (SFS) detection method, the phase angle of the inverter is given by equation 3 – 10 and the DG system control is implemented in the rotating *dq* – frame [4]. The real and reactive power exchange between the DG and PCC are given by: $\boldsymbol{P_L = \frac{3}{2}[V_d i_d + V_q i_q]}$ and $\boldsymbol{Q_L = \frac{3}{2}[-V_q i_q + V_q i_d]}$ respectively. If the PCC voltage is balanced and in steady state i.e. $V_q = 0$, then V_d will be equal to the amplitude of the PCC line to neutral voltage, hence P_L and Q_L will be proportional to i_d and i_q respectively. From the foregoing, $\boldsymbol{P_L = \frac{3}{2}[V_d i_d]}$ and $\boldsymbol{Q_L = -\frac{3}{2}[V_q i_q]}$, this gives $\boldsymbol{i_{dref} = \frac{2P_L}{3V_d}}$ and $\boldsymbol{i_{qref} = \frac{2Q_L}{3V_d}}$, the measured values of $\boldsymbol{i_{dref}}$ and $\boldsymbol{i_{qref}}$ are further processed through the phase angle transformation block where the phase shift is implemented and their respective reference values $\boldsymbol{i^*_{dref}}$ and $\boldsymbol{i^*_{qref}}$ are obtained**.** The phase transformation and inverter controller implemented in MATLAB SIMULINK is shown in appendix two.

4.6 Normal Operation

The ability of the utility grid to maintain the voltage magnitude, frequency and power quality in grid connected mode was investigated. It was observed as shown in figure 4.6, the operation of the system was in a steady state. The THD of the inverter current stood at 2.7% which is smaller than the value of 5% specified by IEEE std. 929-2000. The inverter synchronised with the grid and properly matched with the load power demand. At unity power factor Q_L is zero. In a steady state, $\boldsymbol{Q_{inv}}$ is zero, while Q_{grid} is equal to 0.269 kVAR due to the reactive components of the transmission line.

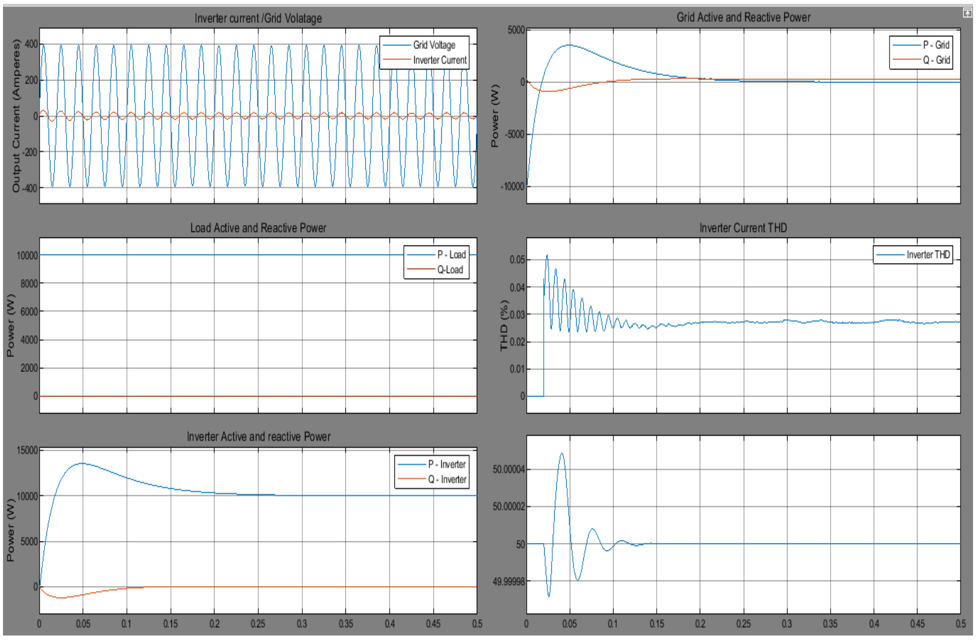

Fig. 4.6 Inverter operation without positive feedback.

4.6.1 Injection of Positive Feedback Signal

In this case, the injection of the feedback signal in grid connected mode does not affect the grid frequency and as such, the frequency shift detection did not act. The effect of the injected disturbance in the island frequency is shown in figure 4.7, the island frequency is moderately higher than the grid frequency, hence the inverter current output is out of phase with the voltage. As a result of the disturbance or feedback signal the inverter injects distorted current accompanied with a dc component into the grid. In response to the disturbance the inverter power factor moves away from unity to lagging power factor and the inverter becomes inductive absorbing reactive power of -0.7742 kVAR. The harmonic components injected into the grid also causes the grid to become inductive and consumes reactive power of -0.4603 kVAR.

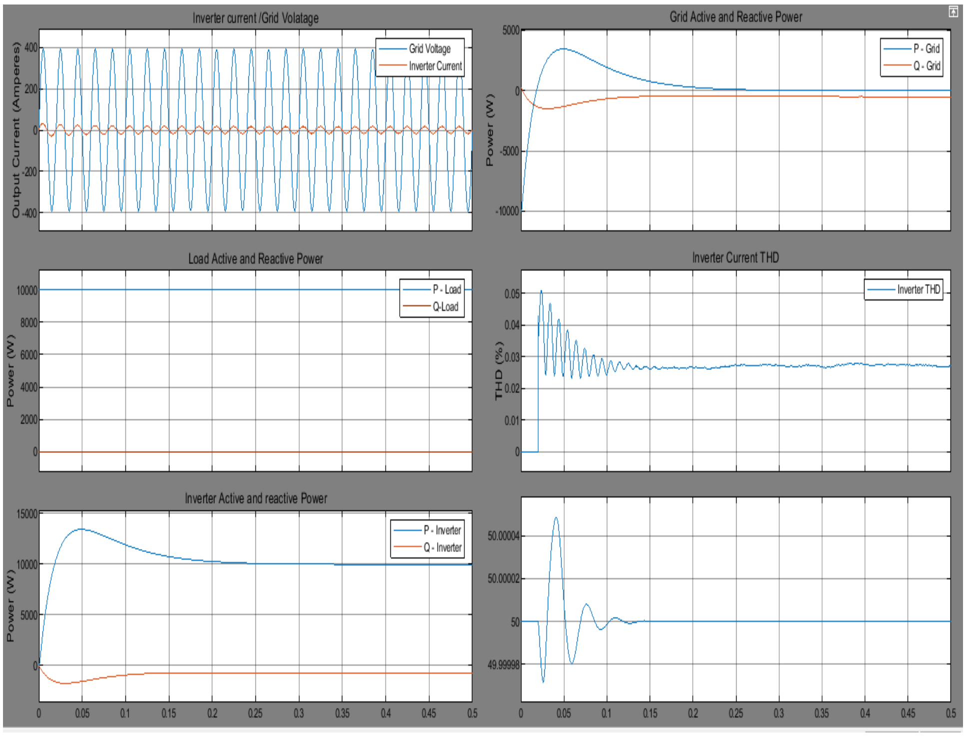

Fig 4.7 Inverter operation with positive feedback.

4.6.2 Islanding Detection Operation

The function of the positive feedback signal is activated as the grid breaker CB-1 opens at 0.1s to simulate grid disconnection. In response to the change, the grid following inverter changes to a grid forming inverter and attempts to build the load voltage. The positive feedback amplification effect begins to increase the frequency, in this case to the upper limit of the trip relay, which is the islanding frequency. The clearing period of the islanding condition is 156 milliseconds which satisfies the 2 seconds requirement [9]. The results are shown in appendix three.

4.7 Non-detection Zone of AFDPF IDM

The non-detection zone boundary of the islanding detection method was calculated from equation 3-14. The upper and lower boundary of the resonance frequency that islanding will occur are 51 Hz and 49 Hz respectively. Islanding can be detected only for a load that has its resonance frequency lying outside the boundary. Failure to detect an islanding situation will occur if the resonance frequency of a load lies within the NDZ boundary.

The simulation results for an RLC load in table 4.1, shows that the resonance frequency of the load (50 Hz) lies within the NDZ boundary, and it would be difficult to detect an islanding situation. The ID method implemented drifts the resonance frequency of the PCC to region outside the NDZ boundary.

5 Discussion and Conclusion

5.1 Discussion

An islanding condition is an unwanted condition when a DG is connected to the utility grid. Hence, it is highly required by regulation to prevent it. The research work studied the Accelerated Frequency Drift with Positive Feedback (AFDPF) also known as Sandia Frequency Shift (SFS). It is an active islanding detection method that makes use of a positive feedback scheme to drift the system frequency to the trip limit of the protection relays to prevent an islanding condition. Compared to other methods of AIDM like active frequency drift and Impedance measurement methods, it does not introduce periodic disturbances that tend to affect power quality or require real power variation like the voltage shift method, making it one of the best and easy-to-implement methods with less effect on power quality.

The effectiveness of the method depends on its parameter design method and load characteristics. Three parameters considered in this study are the selection of the measured frequency to be the upper trip limit of the protection relay, the design of the frequency shift constant, and the chopping fraction. Some other studies showed that the instability criterion eliminates the effect of the chopping fraction, which is independent of the islanding frequency. It was observed that this method causes instability in the implementation of the frequency shift. In this study, the method used to design the shift constant K assumed the chopping fraction to be a constant with a maximum value of 0.046 to achieve the minimum requirement of power quality [37]. Load characteristics such as quality factor and resonance frequency also had to be considered carefully in the design of the shift constant. The chopping fraction was chosen depending on the value of the resonance frequency, if the resonance frequency is greater than the gird frequency, then the chopping fraction is chosen to be positive and if it is less than the grid frequency, the chopping fraction is negative. High load quality factor has a direct correlation with high resonance frequency which could result in a system that could drift towards or remain at resonance when the islanding condition occurs, hence a sizeable quality factor could prevent islanding detection for systems that implement the frequency shift. for the simulation, the test requirement for the quality factor is taken to be 2.5 [11].

The simulation result shows that the inverter output and the load are closely matched, which implies that the allowed two-second clearing time is met by the inverter to recognize islanding and disconnect from the grid. The impact of the feedback could also be seen on both the grid and inverter reactive power. Due to the disturbance, both have negative reactive power, the inverter power factor shifts from unity to a lagging power factor, while the harmonic current injected into the grid causes the grid to absorb reactive power. The loss of the main connection leads to perturbation in the system, and the positive feedback injects a disturbance that pushes the frequency of the inverter to the upper limit of the frequency relay. A ride-through time of 0.1s was implemented in the relay and the relay allows 0.02s for the mechanical process of the relay to trip. The simulation results show the islanding detection capability of the method.

The simulation results are summarised in table 5.1. The Nigerian Electricity Regulatory Commission frequency standard was implemented, having an upper limit of 51 Hz and a lower limit of 49 Hz [6].

The table shows the response of both normal and islanding conditions. During normal operation with the injected positive feedback signal, the utility maintains the magnitude and frequency of the voltage. The current THD contribution is 2.7%, which implies that the impact on power quality from active islanding is not high, according to UL – 1741 standard allowed THD contribution is 5%. When an islanding situation occurs, the detection time was 156ms after disconnection of the utility grid. The frequency at which islanding was detected was 51.4 Hz, this shows that for a system with load quality factor value of 2.5, and resonant frequency of 50 Hz for an AFDPF method having a shift constant k of 0.005 and chopping fraction of 0.046 lies outside the non-detection zone boundary.

Table 5.1 Summary of simulation results.

Mode	**DER Unit**	**Frequency Trip (Hz)**	**Islanding Detection Time (s)**	**Response**
Normal Operation	1	nil	nil	Acceptable
Islanding Operation	1	51.4	0.156	Acceptable

5.2 Results

Overall, in this study, the AFDPF islanding detection method was designed and implemented. The results from the simulation were analysed, and they show that the IDM meets the islanding requirements by IEEE 9292-2000 standard.

Islanding detection standards have different disconnection limits and requirements for implementation. Regulatory organizations like IEEE, IEC, and UL necessitate active islanding by a performance-based type of testing, that only evaluates the dependability of the islanding detection method. The ability to reject disturbance was not investigated extensively. Comprehensive integration of DER that has sensitive voltage and frequency setoff points and short delay periods will threaten the security of bulk power generation. An evaluation of standards to ensure system security by rejecting disturbances will enable DER manufacturers to design and develop a more secure and dependable PV inverter system that can support the grid and as well reject disturbance. This can improve safety in the distribution system and move towards smart grid development. Pre-existing function of DERs such as islanding detection is expected to work alongside new functionalities such as low voltage ride through and frequency ride through (V/FRT) to provide voltage and frequency support during disturbances.

The IEEE 1547-2003 stipulates a disconnection period of 2s for grid tied inverters when fault occurs. From the simulation the run of time (ROT), that is the period between when the grid stops supplying harmonic current and when the inverter is disconnected is 156ms much less than the recommended period. Based on observation of both simulations run-of time and required detection time, earlier islanding detection standards can be reviewed to allow inverters to perform grid support and unintentional islanding detection functions within the specified period of two seconds. This will potentially lead to a trade-off like increased run-off time within the defined two second period.

5.3 Conclusion

Islanding is an unwanted situation in which a grid tied inverter continues to energize the load in the same area EPS after grid disconnection. It is strongly recommended by national and international regulations to prevent such an occurrence. Accelerated frequency drift with positive feedback (AFDPF) also known as sandia frequency shift (SFS) is one of the most significant active detection methods with a remarkable efficiency. It does not inject intermittent perturbations into the grid like other active methods, such as active frequency drift and impedance measurement methods, likewise it does not need real power variation like the sandia voltage shift method.

The frequency shift method applies a positive feedback scheme. During an islanding condition, the system frequency is altered, the ID method attempts to drift the frequency to a region beyond the tripping threshold of the protection system, by altering the frequency of the inverter current to shift in the same direction.

The effectiveness of this method depends on the frequency shift method parameters and attributes of the load. This study examined two main parameters of the method as a trade-off between efficient detection and the disturbance that it can inject into the grid when an islanding condition occurs. The ability of the method was also examined as a function of system load parameters such as quality factor and resonant frequency.

The study was applied to a three-phase grid tied inverter implemented in MATLAB SIMULINK software. The inverter design in the SIMULINK application implemented the islanding detection method with a positive feedback scheme. The simulation results demonstrated the ability of the method to detect islanding effectively. Based on the examination of implemented design, it can be concluded that if the method parameters are calculated properly and load characteristics are designed accordingly, islanding situations will be detected within the stipulated period.

5.4 Recommendations for Future Research Work

- The study is a good starting point for the implementation of the active islanding detection method in the software for practical applications because it has demonstrated good performance.
- Other factors contribute to safer distribution systems with dispersed generation besides improving islanding detection. Stand-alone

applications may become more prevalent to increase the power supply capacity. A widespread issue is that distributed generation using power electronic converters does not contribute to higher short circuit currents. It would be appropriate to do an analysis that addresses the requirements for distributed generation short circuit performance.

- Simulation and testing of grid tied inverter with dual functionality of grid support and unintentional islanding detection operations.

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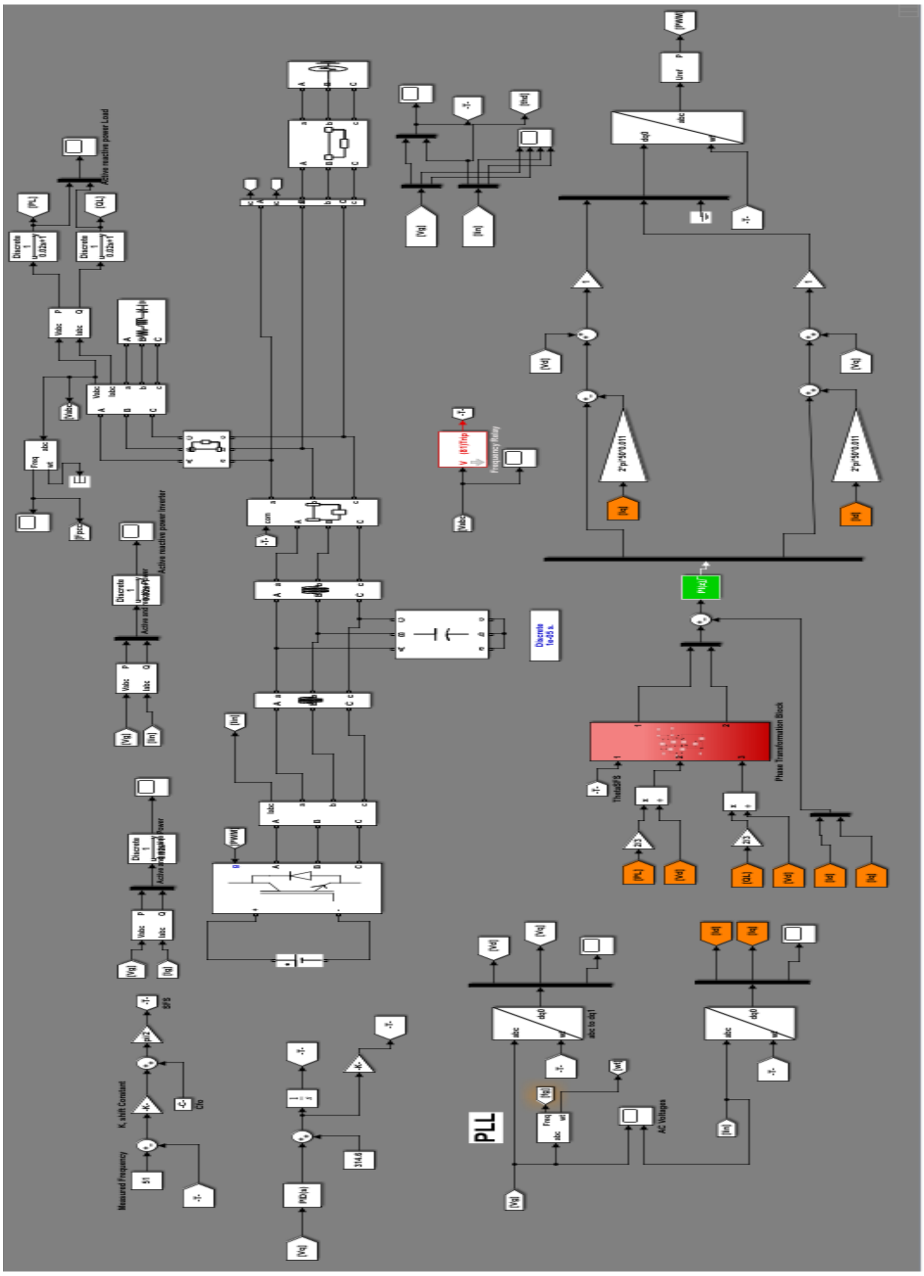
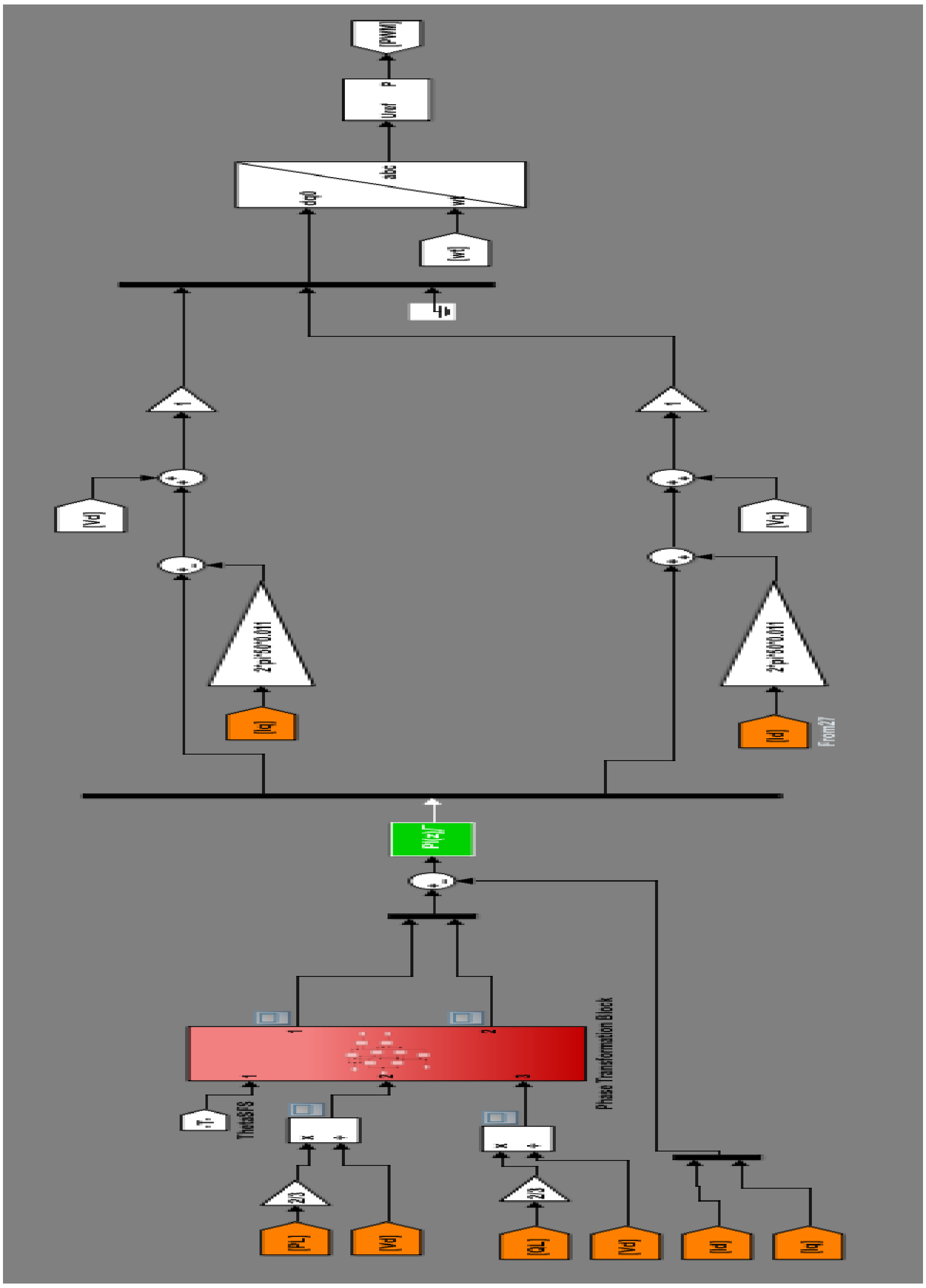
Appendix 1



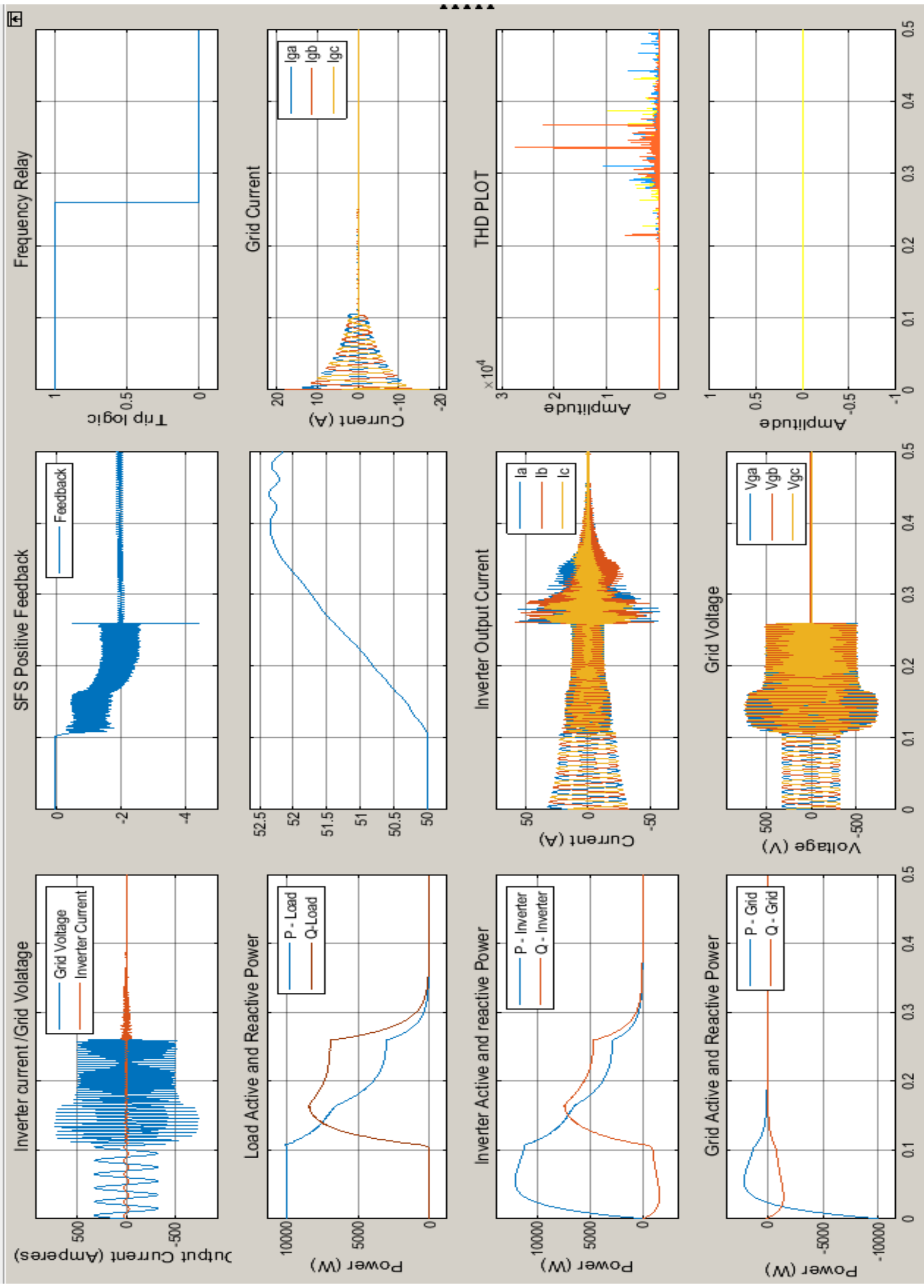
MATLAB/SIMULINK implementation of AFDPF islanding detection method.

Appendix 2



Inverter Control with Phase Transformation implemented in MATLAB/SIMULINK.

Appendix 3



Inverter operation during islanding condition.