ROTATING MACHINE BASED DISTRIBUTED GENERATOR ISLANDING DETECTION AND POWER PRIORITIZATION USING ARTIFICIAL BEE COLONY ALGORITHM

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(Electrical Engineering)

JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

2017

Rotating machine based distributed generator islanding detection and power prioritization using Artificial Bee Colony algorithm

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A thesis submitted in partial fulfilment for the degree of Master of Science in Electrical Engineering in the Jomo Kenyatta University of Agriculture and Technology

2017

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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Dr. M.J. Saulo
TUM, Kenya.

DEDICATION

This piece of work is dedicated to my family for they are my source of inspiration. I owe gratitude to God.

ACKNOWLEDGEMENTS

First, I thank Almighty God for giving me life, strength and motivation to complete this work successfully. I sincerely thank Jomo Kenyatta University of Agriculture and Technology (JKUAT) for giving me the opportunity to pursue my studies in Electrical and Electronics Engineering Department. My gratitude goes to my able supervisors Prof. D.K Murage and Dr. M.J. Saulo for the deep interest they took in this work and for the immense guidance and critical discussions rendered during various stages of my study period. To my family, thank you for your patience, love and unfailing encouragement throughout this period. Finally, thanks to everybody who contributed towards the achievement of this work. God, bless you all.

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LIST OF ABBREVIATIONS

ABC	Artificial bee colony
AFD	Active frequency drift
AI	Artificial intelligence
AVR	Automatic Voltage Regulation
CB	Circuit Breaker
CWT	Continuous wavelet transform
DC	Direct Current
DG	Distributed generation
DFIG	Doubly Fed Induction Generator
DT	Decision tree
DWT	Discrete wavelet transform
DFT	Discrete Fourier Transform
FFT	Fast Fourier transform
FLC	Fuzzy logic Control
FMU	Frequency Measurement Unit
IDM	Islanding Detection Method
IEEE	Institute of Electrical and Electronic Engineers
IPP	Independent Power Producer
kVA	Kilo Volt Ampere
MFs	Membership Functions
MG	Micro-Grid
MRA	multi-resolution analysis
NDZs	Non-Detected zones
OFP	Over frequency protection
OVP	Over voltage protection
PCC	point of common coupling
PJD	Phase jump detection
PLC	Power Line Communication
PSO	Particle Swarm Optimization
PV	Photovoltaic

RMS	Root Mean Square
RLC	Resistor Inductor Capacitor
ROCOF	Rate of change of frequency
ROCOP	Rate of change of power
SCADA	Supervisory Control and Data Acquisition
SDG	Synchronous distributed generator
SFS	Sandia frequency shift
SMS	Slip-mode frequency shift
STFT	Short Time Fourier Transform
SVS	Sandia Voltage Shift
THD	Total harmonic distortion
UFLS	Under Frequency Load Shedding
UFP	Under frequency protection
UVLS	Under Voltage Load Shedding
UVP	Under voltage protection
VSC	Voltage Source converter
WT	Wavelet transforms

ABSTRACT

Currently there is an ongoing deregulation of the power system that has given a new face to the power system by introducing the Distributed generators (DGs) into distribution systems, leading to a bi-directional power flow. One of the major challenges of this system is unintentional islanding of part of the grid. If the occurrence of an unintentional islanding condition is not detected as soon as it occurs or it is completely not detected, it can lead to a total blackout in the entire power system.

To address this challenge, this study is broken into two parts; part one is based on islanding detection of a rotating machine based DGs by using wavelet transform (WT) and fuzzy logic (FL) algorithm. From this analysis, it was observed that there was a quick response to islanding detection due to the changing of the point of measuring of the current signals from the usual PCC to just after the utility circuit breaker. It took 0.2 seconds for this algorithm to detect the occurrence of the island. This is because the islanding detection time is not affected here by the circuit breaker operation time. Thus, making the detection process faster hence the reduction in NDZs in this system.

The second part of this study involved finding the optimal load to be shed and the selection of the buses to be shed using the ABC algorithm. This algorithm was tested on a fourteen-bus system and the obtained result for this system was analyzed and it was satisfactory to draw concrete conclusions. In comparison with other methods of optimization, the proposed algorithm can obtain better optimal solution than many other methods with a fast-computational manner, especially for large-scale systems. Therefore, the proposed ABC algorithm can be a favorable method for solving optimization and prioritization problems in power systems.

CHAPTER ONE

INTRODUCTION

An electric rotating machine can be defined as any form of apparatus which has a rotating member and generates, converts, transforms, or modifies electric power. Examples include a motor and a synchronous generator. Although there are many variations, the two basic rotating machine types are synchronous and induction machines.

There has been a continued and increased use of distributed generation in the power system in response to the increased load demand. This is also due to the associated benefits to both the utility companies and consumers of power. These include increased efficiency of the power supply, minimization of both transmission and distribution capacity upgrade costs among others.

1.1 Problem Statement and Motivation

The islanding detection and control for rotating machine based generators is a more challenging problem in comparison with the inverter-based generators. This is because their options are limited. Unintended islanding operation of sections of power systems is undesirable due to a number of reasons [1]. Some of the reasons are as follows: -

- The distributed generators supplying an islanded system may pose a threat to grid line workers safety
- The islanded system may not be well grounded resulting in high voltage in un faulted phases when an earth fault occurs
- Most importantly, these Distributed Generators (DG) may not be able to maintain the voltage and frequency within desired limits in the distribution system when it is islanded.

Within the established islanded micro grid, there may be a power deficit and eventually there has to be need to shed some of the loads or there may be excess supply within the island and thus we need dummy loads to sink excess power.

Hence the main challenge here is to determine the appropriate and reliable method to optimize the power supply and the load demand within the island and thus maintain the voltage and frequency within the desired limit. It is therefore necessary to design island detection and control scheme that will reduce the Non-Detection Zones (NDZ) without changing the output power quality in power grids and determine the minimum load amount for shedding within the island so that we can optimize the electricity supply to customers.

1.2 Justification

Un-intentional islanding has a number of problems which if not detected well in advance can lead to a lot of damages to both the power grid and electrical power customers' loads. These include its un-ability to maintain voltage and frequency within the required limits; it poses a threat to the line workers safety, grounding problem causing high voltage to other phases when a line to ground fault occurs among others.

Now that the rotating machine based generators are highly capable of sustaining an island unlike the inverter based distributed generators, it is therefore a more challenging problem when it comes to the anti-islanding protection for this rotating machine based generators in comparison with the inverter-based DG [2].

To mitigate this problem, this study is based on islanding detection of rotating machine based DGs by using wavelet transform (WT) and fuzzy logic (FL) algorithm. The position of measuring the signal is changed from the usual point of common coupling (PCC) to after the main circuit breaker. The features of the measured frequency were extracted by the wavelet transform and then used in distinguishing between islanding or non-islanding condition by FL algorithm classifier [1].

In addition to islanding detection, this study also focused on the minimum load amount for shedding within the islanded region and the prioritization of buses so that electricity supply to customers can be maximized using artificial bee colony (ABC) algorithm.

1.3 Recent Researches done in this area

On the side of islanding detection, a number of researches have been carried out. For instance, in [3], Lindula, in his paper, used the Decision Tree (DT) algorithm and combined it with the Discrete Wavelet Transform (DWT) in the detection of the islanding condition. In this study, the features from the measured transient voltage and current signals were extracted using the DWT. The DT method of classification was used to classify the islanding status. Samantha et al in their paper [4], employed Fuzzy Logic algorithm, a transformation from the DT, where the combination of fuzzy membership functions (MFs) and the rule base were used in islanding detection. This method of islanding detection was easy to implement and monitor the system online and was able handle uncertainties like the presence of noise. In [5], however, the band pass filter was used to replace the functions of DWT [6]. This gave out sufficient results.

In [7], Karegar and others used the wavelet transform in islanding condition detection for wind turbines. In their paper, they used the DWT (Db5) in the determination of the best wavelet basis function with accurate results. However, all these methods necessitated the measurement of several electrical quantities, which required much time in detecting islanding.

In 2014, Hossein in his paper, came up with a new fast method for islanding detection based on measuring the utility currents and voltages signals processed by DWT. These features are sum of wavelet coefficients energy and were used for distinguishing the islanding conditions from non-islanding ones [8].

On the other hand, Artificial Bee Colony has been used in solving various application problems both in engineering and outside engineering. The ABC system and its demonstration of the features are discussed by Karaboga and Akay in [9]; additionally, this paper discussed in depth the various algorithms that are made use of in simulating the intelligent behaviors of the artificial bee colony and their applications. The algorithm has also been used to solve certain fundamental problems like the Traveling Salesman Problem, the routing problems among others [10].

An in-depth analysis and study in the performances of the mostly used evolutionary and swarm-based Artificial Intelligence (AI) algorithms that are used for the optimization a very huge set of numerical functions was presented by Karaboga and Akay in [11]. In a different publication Karaboga and Ozturk introduced another application that uses the Artificial Bee Colony [12]. This was mainly used then for clustering data on fundamental engineering problems. The comparisons on the performance of Artificial Bee Colony algorithm with Particle Swarm Optimization (PSO) algorithm is also expounded here [10]. Artificial Bee Colony Programming was described as a new method on symbolic regression which is a very important practical problem.

A set of symbolic regression bench mark problems are solved using Artificial Bee Colony Programming, and then, its performance is compared with the very well-known method evolving computer programs, genetic programming. This terminology, symbolic regression is simply defined as the exercise of coming up with a mathematical model of a system by using finite independent variable values and also their associated values of dependent variables [10]. This is applied in the solution of complicated and advanced prioritization and optimization problems. In nutshell, the ABC algorithm has been used to solve many problems from different areas successfully [13].

Analysis of these research papers indicates that there is more that need to be done so as to ensure that any occurrence of an island is detected as stipulated by the internationally set standards. None of these recent papers gives satisfactory results to guarantee reliability on the power system. Hence through this study the system reliability is improved through the combination of DWT and FL in detecting the occurrence of an island and power prioritization within the island using Artificial Bee Colony algorithm.

1.4 Objectives

1.4.1 General objective

To design a system that is able to fast detect an island and increase power system reliability through power optimization within the islanded micro grid.

1.4.2 Specific objectives

- To design an island detection scheme in SIMULINK/MATLAB that will reduce the NDZ without changing the output power quality in power grids.
- Simulate the designed scheme and use DWT and Fuzzy Logic Control to detect islanding condition
- To optimize power within the island by determining the minimum load amount for shedding in case of undersupply and also determine the size of dummy loads to be used to sink excess power

Note: Dummy loads was used to sink excess power incase power generation exceeds the connected loads in this analysis. Prime mover control is also another possible method of limiting excess power generation which is another area of study on its own.

1.5 Scope

This study is about designing a method of quickly detecting the occurrence of an island in the electric power grid and optimizing the power supply to consumers within the island in case it occurs. This study concentrated mainly on a single rotating machine based generator which includes engine generators, gas turbines and Doubly Fed Induction Wind Generators (DFIG) generators which were analyzed in detail. The models of this research were developed in MATLAB and SIMULINK and many of the standard models available in them were used. Note that this scheme is meant to be used with systems with DGs for islanding detection.

1.6 Thesis Organization

This thesis comprises of five chapters. Chapter one is an introduction to the research topic giving brief background information to the research area, statement of the problem and objectives. Chapter two is the literature review to DGs, Wavelet transform, fuzzy logic and ABC algorithm. In Chapter three, the methodology used in achieving the specific objectives is elaborated starting from the simulation model, feature extraction, classification and power prioritization. Chapter four shows the research results and discussions of implementing the proposed algorithms in islanding detection and power prioritization. Chapter five is the summary, conclusions and recommendations based on the results obtained.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background Information

This incorporation of the distributed generation (DG) to the power system has a number of merits which favours its use. These include and not limited to peak shaving during the time when most loads are connected into the system, saving on the costs of expansion of the transmission and distribution part of the grid, improved system reliability in the power supply, increased efficiency in the power supply, improved power quality and reduced transmission line losses and environmental friendliness of most DGs (excluding diesel distributed generator that are used as back-ups that happen to be the worst performers when it comes to greenhouse gas emissions to the environment). [14] [2]

Generally, there are many types of rotating machine DGs that are in use currently [1]. These DGs include and not limited to the following; Small hydraulic generating units, with and without the speed governor, driving synchronous generators with automatic voltage regulators, diesel units with governors and voltage regulators, wind turbines connected to the system through directly coupled induction generators, and Wind turbines connected to the system through doubly-fed induction generators (DFIG) [15]. Despite the above-mentioned merits of incorporating DGs into the distribution system, they have a major drawback of unintentional islanding. This is shown in figure 2.1. By definition, an islanding condition occurs when the DG continues to power a part of the grid system even after the connection to the rest of the system has been lost, either intentionally or unintentionally [1].

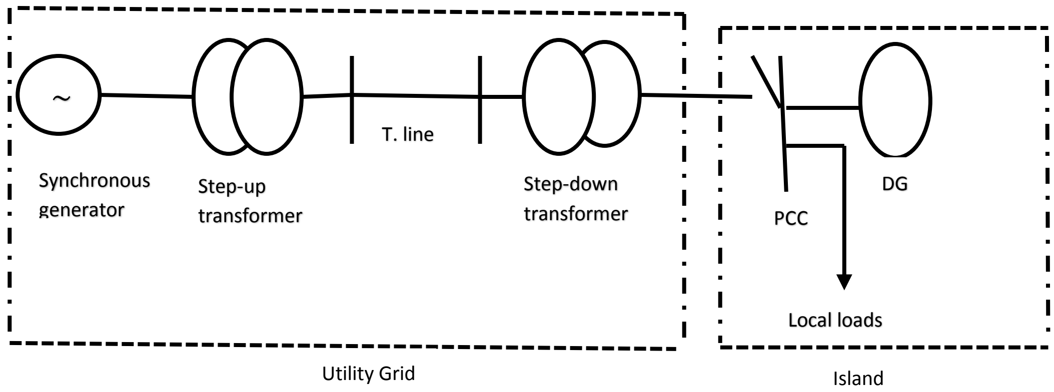

Figure 2.1: Island formation

Currently, the existing power grid systems for most countries in the world are being upgraded to align to the requirements of the smart grid system. There are many reasons that have led to this transformation of the existing power distribution system into the smart grid system as outlined in [17] [18] and are summarized into three as follows:

i. All components that make up the smart distribution and transmission system is supposed to be intelligent enough so as to detect any disturbance or abnormal event in the system and respond to it accordingly and promptly. In case an island is formed, the local distributed generators should have the ability to detect this condition and activate the necessary protection and control devices to take appropriate actions to ensure safe and stable operation of the power system. This is called self-healing.

ii. The supply and distribution of electric power of inferior quality may have both economic and operational negative impacts on both electric utilities and consumers. That is why, it is aimed that electric power utilities should supply consumers with high quality power. Therefore, an early detection of islanding state operation is needed to allow a reasonable time for the intelligent protection and controlling devices to interfere and take appropriate actions to correct the deteriorating situation.

iii. Sometimes, a combination of both renewable and non-renewable based DGs may exist within an islanded distribution system so as to provide a stable DG power system.

Renewable energy based DGs are usually fitted with electronic interfaces which disconnects them from the main grid. Therefore, this may cause stability issues in the grid. Hence fast detection of this unstable operation of the microgrid is needed to evade power blackouts and frequency shifts from the normal.

According to the IEEE standard 1547-2003, it is stipulated that the connected DGs should detect the occurrence of any unplanned for and unintentional micro-grid formed and trip it within two seconds of occurrence, failure to do so, may lead to a number of problems in terms of the quality of power supplied to consumers and other system operational problems [18].

To mitigate this, there are a number of islanding detection methods being used currently. However, each method has its weaknesses and advantages in its application for islanding detection. Hence, there are some parameters often used to check the suitability of any given islanding detection method [1]. These include; the reliability of the method used and its impact to the power grid, its operation time and the cost of implementation to both the DG owner and the power utility companies [20].

These methods of islanding detection are generally categorized into either local or remote islanding detection methods. This is well explained diagrammatically as shown in figure 2.2 below [19].

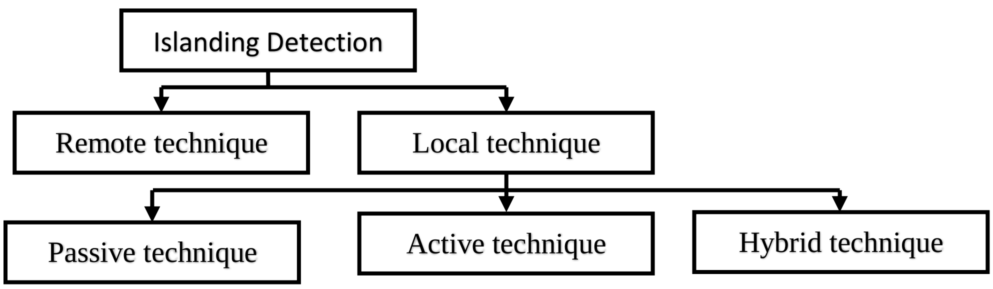

Figure 2.2: Islanding detection methods classification

The remote islanding detection methods include the Power Line Communication (PLC) and the Supervisory Control and Data Acquisition (SCADA) techniques among others. These methods don't suffer from the problem of having NDZs and they have higher reliability in their applications as compared with local islanding detection methods. However, they are quite expensive to implement and making them uneconomical for small and medium power systems [1]. The non-detection zones are obvious problems in the power system islanding detection. They can simply be defined as the loading condition for the system whereby an islanding detection technique would fail to operate in a timely manner to detect an island [21].

On the other hand, the local islanding detection methods are further categorized into active and passive islanding detection methods. The passive techniques are based on measurement of the information at the local site and comparing it with the preset values in order to determine the occurrence of an island. These methods include under or over frequency, under or over voltage, voltage phase jump, voltage unbalance, total harmonic distortion (THD), rate of change of frequency, vector surge, phase displacement monitoring, rate of change of generator power output, comparison of rate of change of frequency [22] among others. These techniques are preferred in islanding condition detection especially when the mismatch between the generated power and the size of the load is very large.

However, when the mismatch is very small i.e. less than 19%, it is difficult to detect the islanding state because the variations in voltage or frequency at the PCC is also very small [23]. The weaknesses of some of the passive islanding detection methods are highlighted in table 2.2 [24].

Table 2.1: Comparison of passive islanding detection methods

METHOD	IMPLEMENTATION SPEED	WEAKNESS
UFP/OFP	Easy but reaction time unpredictable and variable	Large non-detected zones (NDZs)
UVP/OVP		
Phase jump detection (PJD)	Difficult in implementation and hard to choose threshold	Fails to detect islanding when DG power generation matches the power demand of local load
Total harmonic distortion	Easy but hard to choose threshold	Fails to detect island in case of low distortion of voltage and current output of inverter or high quality load
Voltage unbalance		Not applicable to single phase system

The active islanding detection methods have quite small NDZs when compared with the passive islanding detection methods. Despite this advantage, these methods introduce some external signals into the power system in consideration thus lowering the quality of the power being supplied to connected loads. These signals added are very small and they help in detecting the presence of islanding condition. These signals have no effect when the distributed generator is in parallel operation with the electric mains, but they are quickly detected in case of loss of the main grid.

Some of active methods in use currently include; positive feedback for active and reactive power loops in governor and excitation system of synchronous DGs, injection of a negative sequence of current through the interface Voltage-Source Converter (VSC) [25], Sandia frequency and voltage shift methods and harmonic amplification factor, which is based on the voltage change at the PCC [26]. Some of these methods and their drawbacks are shown in table 2.3 [24].

Table 2.2: Comparison of Active Islanding Detection Methods

METHOD	IMPLEMENTATION AND SPEED	WEAKNESS
Impedance measurement	Easy and fast	
Slip mode frequency shift (SMS)	Medium and slow	Ineffective under certain load e.g. RLC resonant load
Active frequency drift (AFD)	Easy and medium	
Sandia frequency shift (SFS)	Difficult and relatively fast	Problem in power quality system stability
Sandia voltage shift (SVS)	Medium and fast	Increase harmonic distortion

In short, the passive and active islanding detection methods have their merits and demerits when separately used to detect the occurrence of an island. It is therefore necessary to merge some of these methods so as to utilize their combined merits as their demerits cancel out. This technique is called Hybrid islanding detection [27].

At the moment, there is no single method for islanding detection that can meet all the conditions in DG system without having some weaknesses. Therefore, the method is normally selected according to the nature of the distributed generator [19].

Generally, in case of the occurrence of intentional islanding, it is the system operators' responsibility to keep as many power customers connected as possible in order to increase overall reliability of the power system. It is therefore important to perform selective and efficient shedding of loads so as to improve power system stability within the island in case there is a deficit within the island and appropriate power sinks (dummy loads) should be put in place in case of over-supply within the island [2]. However, for this to be achieved, there is some challenge of the determination and evaluation of the correct amount of load and which buses that should be shed and also the order in which they will be shed considering their priority. At the same time, if too much load is shed from the system, there is a consequence of having sudden changes in the system voltage profile that triggers transients in the power system [28].

2.1.1 Islanding Condition and its Impacts

Despite the above mentioned many merits of incorporating distributed generators in the power distribution system to supplement what is provided by the mains, as mentioned before, these DGs have a main weakness of unintentional islanding. The islanding condition occurs within the power system when the DG continues to power a part of the grid system even after the connection to the rest of the system has been lost, either intentionally or unintentionally [1].

This unintentional islanding operation mode is not desirable to both the power utility companies and to the electric power customers because of a number of reasons. These include;

i. It Poses a health and safety danger to the utility company maintenance team
ii. The islanded system may not be properly grounded resulting in high voltage in healthy phases when an earth fault occurs in the system. This creates and compromises power quality being supplied and associated problems for customer’s load
iii. It leads to out of phase power re-connection of the re-closer switches
iv. The DG may not be able to maintain the voltage and frequency within desired limits in the distribution system when it is islanded thus leading to damaging both utility and consumer devices and equipment

2.1.2 Unintentional and Intentional Islanding

The cascading failures and blackouts are the most significant threats to the security of power systems. For many years now, the world has encountered many power blackouts as a result of these cascading failures [29]. By definition, a cascading failure is a process where one failure in the system leads to successive failure of other elements of the power grid.

These cascading scenarios possess great risks towards the integrity of power system network, and this may finally lead to the splitting of the power system into various unintentional islands. Furthermore, these unintentional islands created may sometimes encounter active or reactive power deficiency, which may lead to frequency, angle, or voltage instability. These frequency, angle, or voltage instability may further cause the tripping of other regions if not controlled properly. During such condition, the secure and reliable operation of the whole power system network in an interconnected mode may be very difficult to control. It may result in the propagation of these instabilities in other stable parts of the network. Hence, intentional or controlled islanding is then utilized as a preventive measure to minimize the losses caused by unintentional islanding of the power system.

Intentional islanding is the process of willingly splitting the grid into separate controllable islands [30]. Due to its economic and technical benefits, there has been an increase in the research in this field of intentional islanding operation of DG systems currently and in the recent past. The intentional islanding of some selected parts of the power grid is beneficial because it separates the faulty sections of the power grid from the stable sections.

Thus, by so doing, the entire power system grid is split into small controlled islanded regions for easy handling and control. In such scenario, each islanded region should have enough generation to supply the connected loads in order to remain operative and stable [29]. Figure 2.3 shows a good example of the power system that has been divided into three island regions after successful splitting.

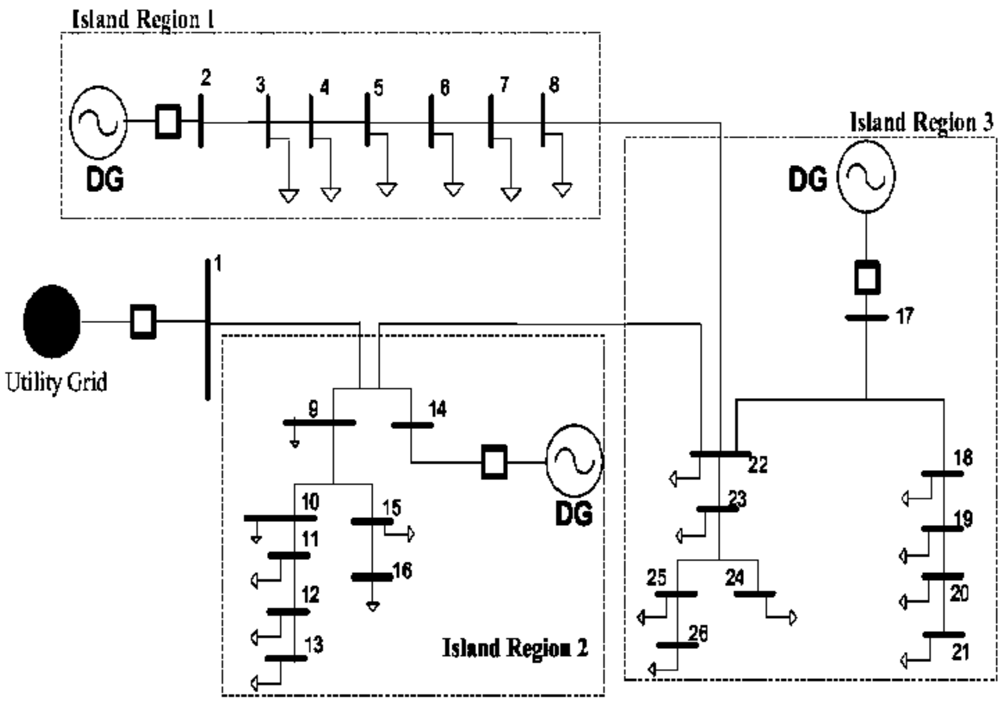

Figure 2.3: Islanding splitting example

It should also be pointed out that intentional method of islanding is very important as it can prevent the entire power system from a total collapse. However, the time and sequence of islanding and how to ensure successful islanding, remains not clear to many engineers. That is why the correct identification and separation of power system into small stable islands is a quite challenging exercise that is currently being researched the world over by researchers in this field.

2.1.3 DG network islanding from utility perspective

Utility companies have a more pragmatic point of view of distributed generation islanding [31]. Their main mission is to improve the distribution level customer service reliability especially in regions where the reliability is below customers' needs. Through the use of DGs in these regions, the customer reliability will improve and at the same time the additional power from the DGs can even be sold back to the main electric power grid especially if it surpasses the load demand in that region.

However, the intentional islanding will not be permitted without prior studies on the required network upgrades. Some examples of these studies include and not limited to the following:

- Reactive and real power profile and its control control
- Prior planning for proper islanding
- The maximum and minimum feeder loading
- The Islanding load profile
- Maximum and minimum profile of the voltage
- The sensitivity of protection and
- The inertia of the DG

One of the specific examples of the above studies is the determination of how the substation auto reclosers of the circuit breakers and the main line reclosers may be disabled and other protection devices may need to be removed to allow proper coordination of utility sources and DG sources [31].

In addition to the above mentioned necessary studies, the maintenance times of the power system may also increase. This is because the power utility workers will not only need to lockout the utility lines but they will need to take additional time to lockout all the installed DG lines. The following are some of the necessary installation studies an Independent Power Producer (IPP) must complete in order to be able to island:

- The unintentional islanding and the planned islanding studies.
- The reliability studies.
- The quality of power studies.
- Utility company equipment upgrades analysis studies
- Both safety and protection reviews and
- The commercial benefits studies

It is therefore clear that the DG designing costs to be capable of islanding or to be simply installed into the main electricity utility owned network requires an extensive and expensive engineering and business analysis. This may be far beyond the financial range of smaller and medium DG electrical energy suppliers.

2.2 DG Islanding and Islanding Detection

2.2.1 Distributed Generation

Distributed Generation (DG) in simple terms refers to the generation of electric power close to, or at the point of consumption. There are many different types of distributed generation machines being utilized in power system grid currently. The first group of DGs includes the synchronous distributed generators which are most commonly used with the internal combustion engines, gas turbine generators, and in small hydro-electric dams. On the other hand, asynchronous DG generators use transistor switched components like those used in inverters. Asynchronous generators are most commonly used with micro turbines, photovoltaic, and fuel cells. A comparison of each type of generation system is shown in Table 2.4 [19].

Table 2.3: Types of DG and typical capacity

Technology	Typical capacity	Utility interface
Photovoltaic	10VA to several VA	Inverter
Wind	10VA to 500kVA	Induction and synchronous generators. Inverters
Geothermal	100VA to several MVA	Synchronous generator
Micro hydro	100VA to several MVA	Induction or synchronous generator
Reciprocating engine	1000VA to several MVA	Induction or synchronous generator
Combustion turbine	1000VA to several MVA	Synchronous generator
Combined cycle	1000VA to several MVA	Synchronous generator
Fuel cells	10KVA to several MVA	inverter

2.2.2 Advantages of Distributed Generations

Due to its merits, the distributed generators have been widely used in the distributed systems to supplement the mains power supply especially during islanding situations. Some of their advantages include [32];

- The distributed generation (DG) resources are flexible as they can be located at several positions within the utility's distributed regions. This ability of the DG equipment to be placed at many locations provides the utility companies with a lot of flexibility to match the DG generators to the system needs.

- The use of the DG generators improves the reliability of the power grid by placing the needed additional DGS closer to the load consumers. This minimizes or eliminates any impact from the transmission and distribution system disturbances. It also helps in reducing congestions on the local grid during peak-period. Furthermore, many DG units at one site can improve reliability by dispersing the capacity across several units instead of a single large central plant.
- The power utility and load demand can be served by power delivery points at local points thus significantly reducing the susceptibility to service interruption from imported electricity supplies due to natural disasters, supplier deficiencies or interruptions, or during acts of terrorism.
- The placing the DG generating units on the low-voltage bus of the existing transmission and distribution substations leads to the reduction in Loading of the power transmission and distribution Equipment especially during peak hours. This leads to the increases the equipment lifespan thus increasing the planned substation up grades durations.
- It reduces the need to construct new transmission lines or to upgrade the existing ones as a result of increasing load demand.
- Reduction in transmission and distribution line losses that result from increase in transmission currents
- Improve power quality and voltage profile of the system.

2.2.3 Disadvantages of distributed generation

The use of DGs has also few demerits. These include; it introduces harmonics into the power system, deviation of direction of power flows from the conventional, the power production is uncertain and finally safety and protection to personnel issues among others.

2.3 Island detection methods

Various techniques have been developed to detect the occurrence of the islanding condition in the power system. These techniques are broadly classified into two categories; that is, remote and local islanding detection methods.

2.3.1 Remote islanding detection methods

The remote islanding detection methods make use of the signal transmission between the main power grid utilities and the distributed generators which carry the information of the status of the power system [19]. When their performance is compared with local islanding detection methods, these techniques are usually more reliable. However, they are expensive to implement and hence prove to be uneconomical for small power grids. Some of the remote islanding detection techniques are briefly highlighted as follows:

2.3.1.1 Power Line Signaling Islanding Detection Scheme

This method of islanding detection uses the utility electric power line to transmit the signals conveying of either islanded or not islanded status of the system. The facilities and equipment that are used in this form of communication includes a signal generator placed at the substation that is coupled into the electric network where it continuously broadcasts signals giving the status of the system. This is diagrammatically elaborated in figure 2.4 below.

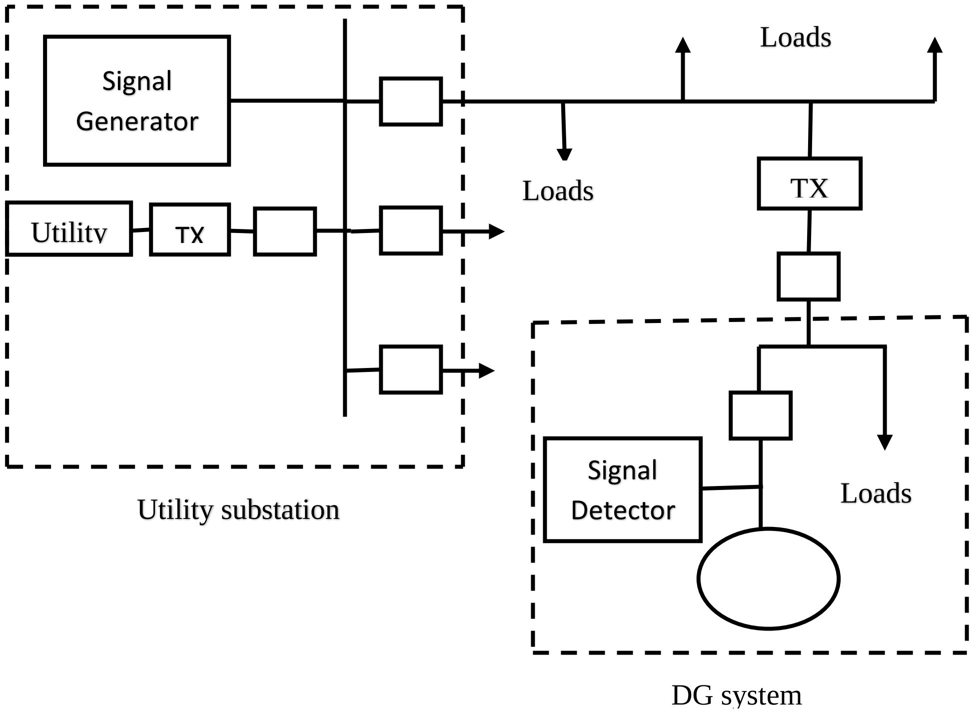

Figure 2.4: The DG power line islanding detection scheme

In order to minimize interference with the signals from other carrier technologies like Automatic Meter Reading (AMR) which is as a result of the low-pass nature filters of the power system, these communication signals need to be transmitted and conveyed near or below their fundamental frequency [29].

Therefore, the Distributed Generators are then fitted with appropriate signal detectors which decode these signals which have been transmitted over the power line. Under the normal operating conditions, these signals are received by the DGs when the system remains connected to the main grid. However, if an islanding condition occurs, these transmitted signals are cut off because of the substation breaker opening and the signal cannot be received by the DG, hence indicating an islanding condition [33].

Some of the advantages of this method of islanding detection include its simplicity of control and high reliability. In a radial system of communication, only one transmitting generator is used which continuously communicates the status to a number of DGs that are connected to it in the network. The only instances that the message is not received by this DG is when the interconnecting circuit breaker has been opened, or if there is a fault in the line which hinders the transmitted signal.

This method also has a number of significant disadvantages that cannot be ignored. For instance, it has difficulties when it comes to the practical implementation. To connect this device to a substation, it requires a high voltage to low voltage coupling transformer. A transformer operating in this kind of voltage and capacity can be very expensive that may be very undesirable for small electric power networks.

Secondly, if this signaling method is applied to other systems that are not radial, it will require the use a number of signal generators. This is well elaborated in figure 2.5 where the three feeder busses connect to one island bus. To implement this kind of the system, as opposed to a simple radial system, it will cost slightly more.

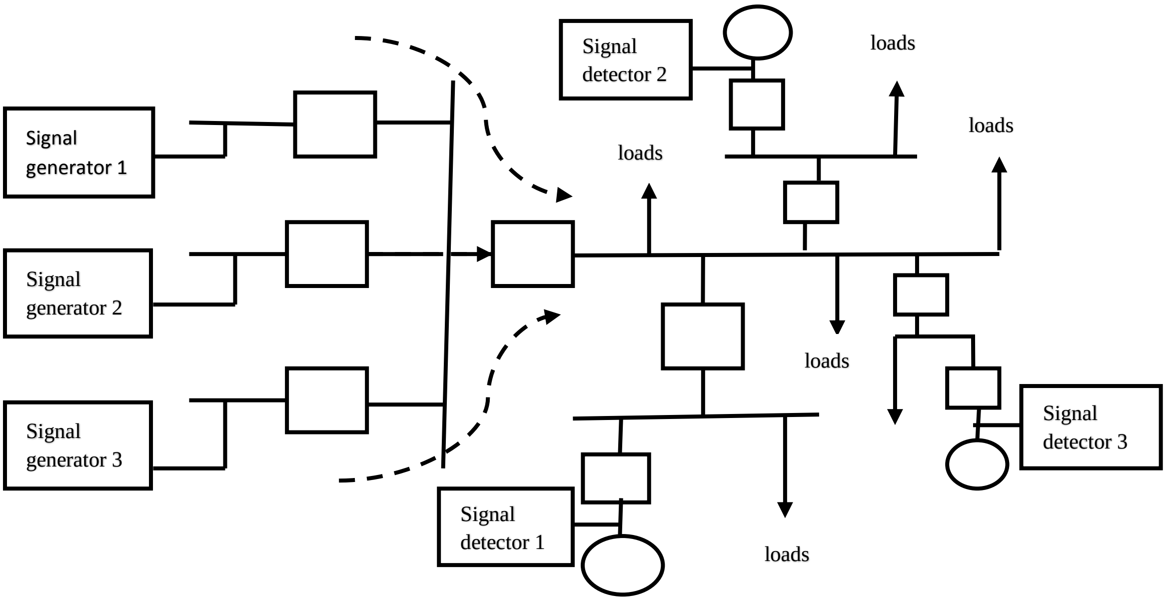

Figure 2.5: DG for multi power line islanding detection scheme

In addition to the above highlighted challenges of the power line communication, this method has another problem associated with the complexity of the network and its affected networks. A perfectly radial network with one connecting breaker is simple example of island signaling; however, more complex systems with multiple utility feeders may find that differentiation between upstream breakers very difficult.

2.3.1.2 Transfer Trip Islanding Detection Scheme

The main purpose of the transfer trip islanding detection scheme is to monitor the status of all the circuit breakers and re-closers in the network that could island a distribution system [34]. Supervisory Control and Data Acquisition (SCADA) systems can be used for this purpose.

Transfer trip method has one distinct advantage similar to the Power Line Carrier (PLC) Signal. That is, it is a very simple concept and it is easy to be applied. With a radial topology that has few DG sources with few circuit breakers, the system state can be sent to the DG directly from point of monitoring point. This is one of the most common schemes used for islanding detection as elaborated in [35]. This method is shown diagrammatically in figure 2.6 [19]

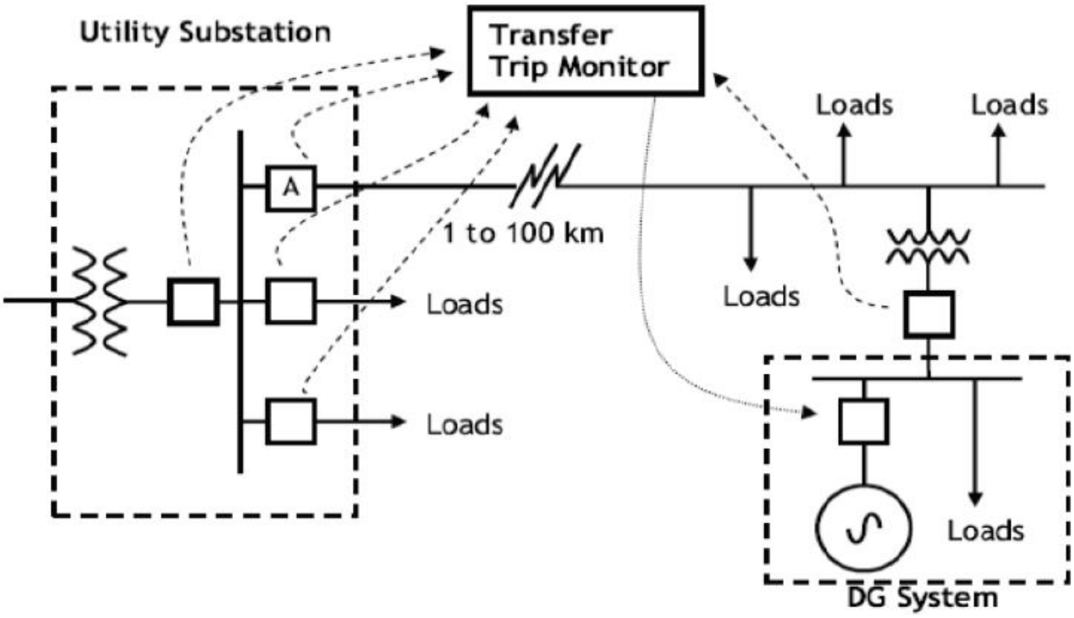

Figure 2.6: The transfer trip method of islanding detection

2.3.1.3 Operation

Under normal operating condition, all monitored circuit breakers are in their normal closed position and hence no signal is sent to isolate any section. However, in case of the detection of a disconnection at the substation, this transfer trip system determines which areas are islanded and sends the appropriate signal to the DGs, to either remain in operation, or to stop the operation.

2.3.1.4 Disadvantages

This method of islanding detection has some weaknesses that limit its application. These include; it becomes difficult and costly to control when the system grows and becomes large. In addition to this, as the power system grows and increases in complexity, the transfer trip method may also become inappropriate.

In response, this calls for relocation or upgrading of the entire power system. Reconfiguration of the transmission devices before and during the planning stages of the DG network is crucial in order to predict whether the network is likely grow or whether many DG installations are planned [36].

In addition to this, the other weakness of this system of islanding detection is in its control. As the substation continuously gains control of the distributed generation, this can make the DG operator to lose control over the power producing capability and this will call for special agreements with the utility companies. However, if the transfer trip method is implemented correctly in a small and simple network, there are usually minimal or no non-detection zones in the network operation [36].

2.3.2 Local Detection Techniques

Local Islanding Detection Methods (IDMs) can be classified into three categories. That is; passive, active and hybrid islanding detection methods.

2.3.2.1 Passive Islanding Methods

Passive anti-islanding detection methods are used to monitor electrical parameters such as voltage, frequency, rate of-change of frequency, phase displacement and harmonic distortion at the PCC of the DG. When the DG is islanded, those parameters change and trigger the disconnection of the distributed generator. Passive methods can be generally being classified as shown in figure 2.7 [37].

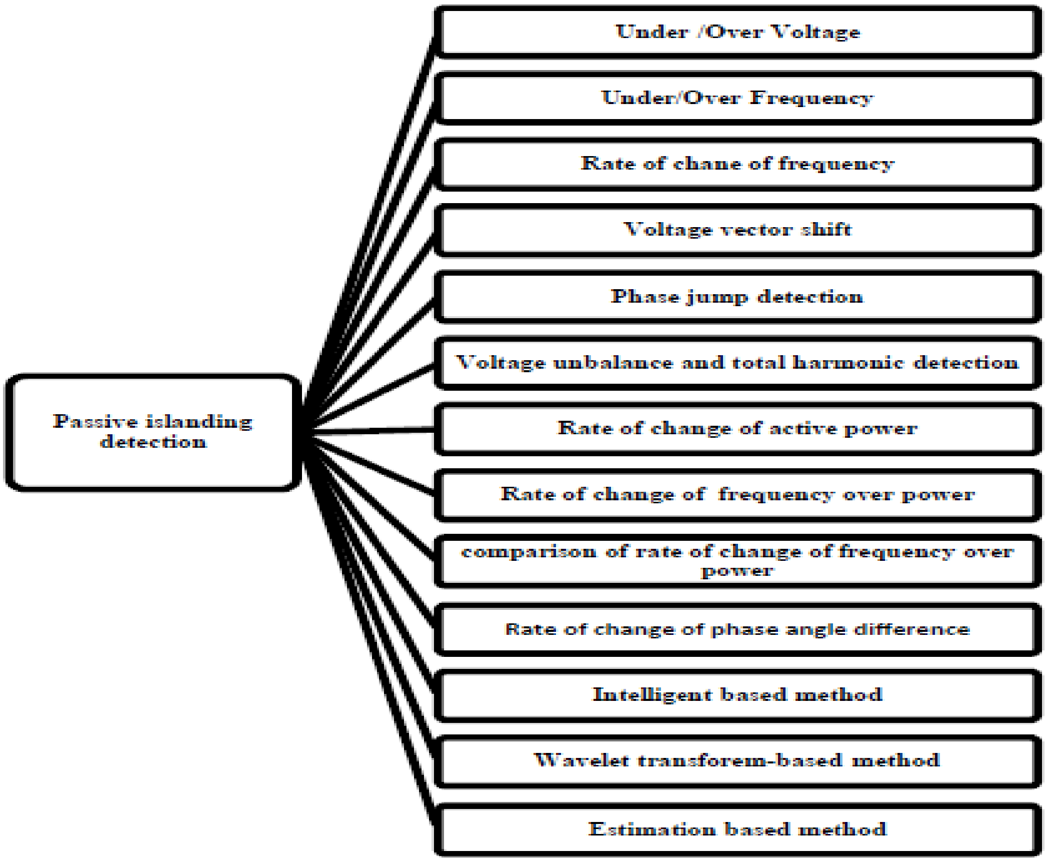

Figure 2.7: Classification of passive islanding detection methods

The parameters mostly used to detect islanding conditions here are frequency and voltage levels in the system. One of the main passive islanding detection methods is the Over or Under Voltage and Over or Under Frequency (OUV/OUF). These methods are some of the earliest used passive islanding detection techniques that were adapted to the protection and distribution system. These techniques simply monitor the systems voltage and frequency in order to determine whether or not an islanding condition has taken a place or not [38].

The protection relays that are used in these techniques are usually placed on the distribution feeder to determine the different types of abnormal conditions. UVP/OVP and UFP/OFP are used to monitor if the grid voltage or frequency exceeds the limits imposed by the relevant standards [39]. Thresholds for UOV and UOF can be calculated as follows:

$$\left(\frac{v}{v_{max}}\right)^2 - 1 \leq \frac{\Delta p}{p_{DG}} \leq \left(\frac{v}{v_{min}}\right)^2 - 1 \qquad 2.1$$

$$Q_f\left(1-\left(\frac{f}{f_{min}}\right)^2\right) \leq \frac{\Delta Q}{p_{DG}} \leq Q_f.\left(1-\left(\frac{f}{f_{max}}\right)^2\right) \qquad 2.2$$

Where; V_{max} is the maximum voltage threshold for the relay,

V_{min} is the minimum voltage threshold for voltage relay operation,

f_{max} is the maximum threshold frequency for relay operation and

f_{min} is the minimum threshold frequency for relay operation.

When the set frequencies and voltages limits for a particular relay is exceeded, the relay is triggered into operation, and signals the appropriate circuit breaker to open its contacts and hence isolate that section of the power system

2.3.2.1.1 Rate of change of the System output power

The rate of change of system output power, $\frac{dp}{dt}$, is insignificant, and does not have any effect when the DG is operating in parallel with the mains. However, this, $\frac{dp}{dt}$, at the DG side, once it is islanded from the main grid, will be much greater than the rate of change of the system output power before the DG is islanded for the same rate of load change [40]. Hence, these changes can be used in the determination of island formation in power systems. It has been found that this method is much more effective when the distribution system with DG has unbalanced load rather than balanced load.

2.3.2.1.2 The Rate of change of System frequency

The rate of change of the system frequency, $\frac{df}{dt}$, will be very high when the distributed generation is islanded from the main grid than when it is not islanded. This rate of change of frequency (ROCOF) can be expressed by the following equation.

$$\frac{df}{dt} = \frac{\Delta p}{2HG} * f \qquad 2.3$$

Where, *p* is *DG* side power mismatch,

H is the moment of inertia for DG system and

G is the rated generation capacity of the DG system.

Generally, large power systems have large inertia, H, and rated generation capacity ,G, while small power systems have small H and G hence giving larger value for $\frac{df}{dt}$. The ROCOF relay monitors the waveforms of voltage of the system and will operate if the ROCOF is higher or less than the setting for a given duration of time. The setting of this relay has to be chosen in such a way that the relay will only trigger in case of the occurrence of islanding condition but not for small load changes.

This method of islanding detection is very reliable and accurate when there is large power mismatch but it becomes inaccurate or fails to operate completely if the generator's output capacity matches with its local loads. However, a merit of this particular method along with the rate of change of power algorithm is that, even though they fail to operate when the connected load is equal to the generation of the DG, any subsequent local load changes would generally lead to the detection of the islanding as a result of load and generation differences in the power islanded system.

2.3.2.1.3 The Rate of change of frequency over power

From the recent studies of the different power systems, the Rate of Change of Frequency over Power (ROCOFOP), in small and medium power generation systems is larger than that of the power system with bigger power generating capacity. The ROCOFOP makes use of this concept to determine the formation of the islanding condition. Furthermore, the studies done so far show that for a small power mismatch between the DG and the connected local loads, the rate of change of frequency over power is much more sensitive than rate of frequency over time [19].
Under normal operating conditions, the ROCOFOP is very small and thus goes unnoticed for DGs connected in parallel with the main grid. However, when an island occurs, the ROCOFOP is very large and hence this can be used is the determination of islanding formation when DGs are connected to the mains.

2.3.2.1.4 The Voltage Unbalance Islanding detection method

The moment an islanding condition occurs in the power system, the connected DG has to supply the connected loads within that island formed with the required power. If these changes in the loading are large and greater than the generation capacity, then the islanding condition is easily detected by monitoring the following parameters:

- The magnitude of the voltage
- The displacement of the phase angle
- The frequency changes

However, if these load changes are quite small, this method may not be effective or it may completely fail in detecting the islanding condition. As the distribution system networks mainly comprise of single-phase loads, it is highly possible that the islanding condition will change the load balance of the DG supplying that island. Furthermore, even though the change in DG loads is small, voltage unbalance will occur due to the change in network condition [19].

2.3.2.1.5 Harmonic Distortion Method

The harmonic distortion can be defined in simple terms as the change in the signal waveform from the normal and ideal sinusoidal waveform. Hence, the variation of the load can lead into the flow of different harmonic currents in the power network. Therefore, monitoring the Total Harmonic Distortion (THD) in the Distributed Generators (DGs) is one of the main methods of detecting the occurrence of an islanding condition in the system. Mainly, the third harmonic component in the voltage signal can give a clear indication of the islanding condition.

2.3.2.2 Active Islanding Detection Methods

The active islanding detection techniques depend on injecting some perturbations and signal disturbances into the distribution sections of the power system to facilitate significant changes in the power system parameters in consideration and hence allow easy detection of the island the moment it occurs. If the injected perturbation is able to affect the parameters of the network, within prescribed requirements, island situation is detected and the connected DG in that region is tripped.

These active methods of islanding detection have small NDZ when compared with passive methods. However, this method results in degrading the power quality because they introduce perturbations in the voltage and/or current at predefined intervals which defeats the objective of having digital grade power quality attribute as aimed in smart grid [41]. Active method can be classified into:

- Reactive power export error detection
- Impedance measurement method
- Phase (or frequency) shift method
- Active Frequency Drift method
- Active Frequency Drift with Positive Feedback Method
- Adaptive Logic Phase Shift method and
- Current injection with positive feedback method

2.3.2.3 Hybrid Islanding Detection Schemes

The hybrid methods of islanding detection are normally the combinations of both active and passive techniques. They introduce perturbations through active methods only after the detection of the island by passive scheme and thus, reducing the amount of perturbations injected into the system. However, the main weakness of these methods is that they need longer time in order to detect an island as compared to active and passive methods used separately. The active technique is implemented only when the islanding is suspected by the passive technique [19]. These can be classified into:

- Technique based on voltage and reactive power shift
- Technique based on positive feedback and voltage imbalance

2.3.3 Comparison of Island Detection methods

The table below shows the comparison based on islanding detection methods [42].

Table 2.4: Comparison of Island Detection Methods

Characteristic	Local method			Remote method	
	Passive	**Active**	**Hybrid**	**Utility**	**Communication**
Principle of operations	Uses monitoring of local voltage, current, frequency and harmonic sensing at pcc	Uses disturbance signal injection from DG to drive the operating point of the system towards the frequency/voltage trip limits	Combination of active and passive methods	Based on installed specific equipment such as impedance on the utility side to modify the impedance that can be seen at the PCC during islanding	Uses communication between the grid and DGs by installed communication equipment
NDZ	Large	Small	Small	None	None
Response time	Short	Slightly shorter than passive method	Longer than active method	Fast	Faster
Effect on distribution system	None	Direct influence on power system such as voltage fluctuation	Lower than active method	None	None
System cost	Low (minimal hardware)	Medium (required additional equipment and circuitry)	High	Very high	Extremely high
Effectiveness	Depends on consumer and supply condition (less efficient on source load balanced condition)	Effective (can detect islanding even on source load balance condition	Very effective	Very effective	Most effective
Multiple DGs operation	Possible	Not possible	Possible	Possible	Possible
Influence by the number of connected inverter	None	Yes	Yes	None	None
Effect on power quality	No degradation	Degraded (reduced power quality, system transient response, voltage stability and others	Degraded but much lower than active method	No degradation	No degradation

The table indirectly shows the common advantages and disadvantages of passive, active, hybrid and remote methods.

Passive method is the basic requirement of grid connected DG because this method is economical and practical. In addition, passive methods cause no degradation to power quality and are easily implemented. The demerits of passive methods are the large NDZ and difficulties of threshold setting. Moreover, passive method is not guaranteed for all load conditions, especially in load-supply balanced condition.

Active methods are developed to reduce NDZ of passive methods, thus most of the active methods have very small NDZ (even eliminated) compared to passive methods, except in cases of high Q factor loads. But the concept behind the active methods is to drive the operation point of the system towards UFP/OFP and UVP/OVP trip limits, by destabilizing the system. Consequently, active methods can degrade the system stabilization and power quality.

Communication based islanding detection has perfect performance but the system and operation cost is extremely high, due to the additional telecommunication devices and sensors installed at utility company side. Hence, these methods are usually applied to large scale systems with sensitive power loads, where electric quality and system stabilization are emphasized instead of system cost.

Therefore, with the objective to solve problems of those three common methods, hybrid detection methods have been proposed to reduce NDZ, provide better power quality and cheaper system cost.

2.3.4 General Islanding Detection steps

Now that the islanding condition should be detected as fast as possible, researchers are tirelessly looking for a better method of identifying this condition and either switch off the DG or optimize the power produced within the island. That is why the signal processing tools come in handy here in extracting the features from measured signals. Then artificial intelligent tools are used to classify the extracted signals to either islanded or non-islanded condition. The general steps usually followed in determining islanding state classification are shown in figure 2.8.

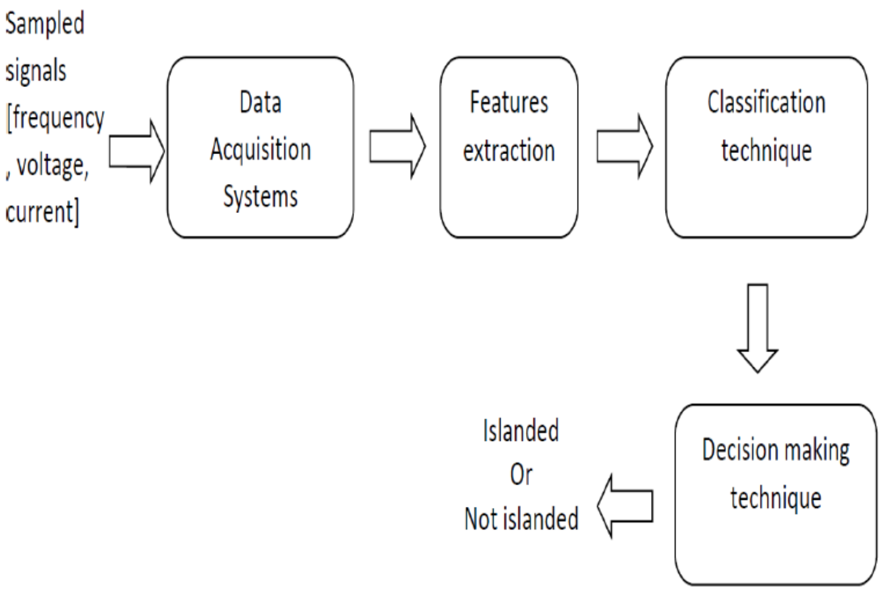

Figure 2.8: General islanding detection steps

2.4 Islanding Detection Standards

There are many international standards used to guide power utilities in designing and operating an island system. Table 2.6 summarizes these standards [29].

Table 2.5: Islanding detection standards

STANDARD	Q_f	ISLANDING DETECTION TIME	FREQUENCY RANGE	VOLTAGE RANGE
IEC 62116	1	t<2 s	$(f_0$-1.5hz)≤f and f≤$(f_0$+1.5hz)	85%≤V≤115%
UL 1741	2.5	t<2 s	59.3hz≤f≤60.5hz	88%≤V≤110%
IEEE 1547	1	t<2 s	59.3hz≤f≤60.5hz	88%≤V≤110%
KOREAN STANDARD	1	t<0.5 s	59.3hz≤f≤60.5hz	88%≤V≤110%
IEEE 929-2000	2.5	t<2 s	59.3hz≤f≤60.5hz	88%≤V≤110%
VDE 0126-1-1	2	t<0.2 s	47.5hz≤f≤50.5hz	88%≤V≤110%

For a satisfactory operation of islanding detection method, the IEEE 1547-2003 standard has been a recommended standard test system frame as shown in figure 2.9.

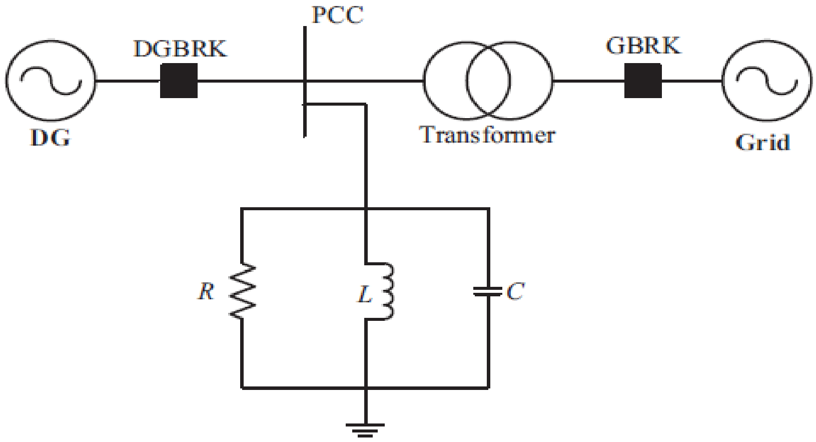

Figure 2.9: IEEE 1547 islanding detection test frame

In this given test frame, the islanding event can be simulated by opening the grid circuit breaker (GBRK). The type of the load connected can affect the performance of islanding detection method. As per the IEEE 1547-2003 test frame, such a load can be modeled as a parallel RLC circuit. This circuit is mostly used, as it does not raise more difficulties for the islanding detection methods as compared to other combinations of circuit. The values of R, L, and C for the unity power factor load can be determined using the following equations:

$$R = \frac{V^2}{P} \quad 2.4$$

$$L = \frac{V^2}{2} * \pi * f * Q_f * P \quad 2.5$$

$$C = Q_f * \frac{P}{2\pi f V^2} \quad 2.6$$

$$Q_f = R\sqrt{\frac{C}{L}} \quad 2.7$$

Where

$\boldsymbol{Q_f}$ is the quality factor, which is the ratio of the amount of energy stored in the load's reactive elements to the amount of energy dissipated in the load's resistance,

R is the system resistance,

V is the voltage,

P is the power,

L is the inductance,

f the frequency and

C the capacitance of system.

Q_f is normally given from manufacturer's data sheets. Given any parameter, the others can be determined by computation using the above formulas.

2.5 The Wavelet Transform

A wavelet can be defined as a small wave. Wavelet transform is a time-frequency representation of any signal. A wavelet transform (WT) convert a signal into a series of wavelets that are used for analyzing waveforms that are bound in both frequency and time. Alternatively, WT can be defined as a collection of functions that are used for analyzing non-stationary signals in MATLAB platform. It is actually a new mathematical tool developed for analyzing non-stationary and fast changing wide-band signals. Unlike, all Fourier-based transforms (Discrete Fourier, Fast Fourier or STFT) which suffer fixed size window, wavelet transform is able to provide variable size window and hence time and frequency resolutions are not compromised. Figure 2.10 provides a comparison between (a) Fourier Transform, (b) Short-Time Fourier Transform, and (c) Wavelet Transform.

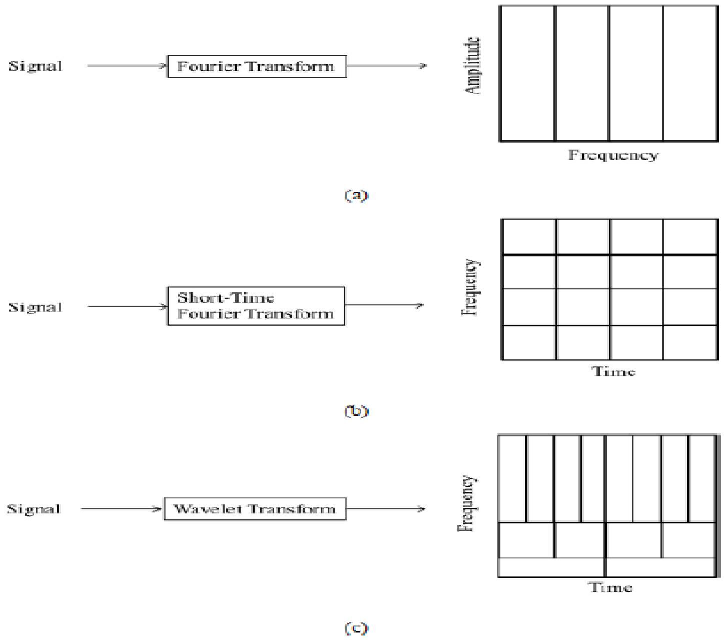

Figure 2.10: Time and frequency characteristics

As it can be seen from figure 2.10, the use of Fourier transform (FT) in signal analysis gives only the frequency characteristics of the signal without any information regarding the times at which the disturbances occur. On the other hand, Short-Time Fourier transform (STFT) has the ability to give both the time and frequency information of the signal being analyzed. However, in case one wants to increase the resolution in one domain, that's frequency or time, will have to compromise the resolution of the other domain since the STFT has a fixed window size.

This shortcoming of the Short-Time Fourier transform is well taken care of in the Wavelet transform (WT). The WT has the ability to extract both frequency and time characteristics of the signal since it has a variable window size.

The main advantage of WT is that it needs not to assume the stationery or periodicity of a signal as it is able to simultaneously distinguish both time and frequency signal information of the analyzed signal. This is due to its multi-resolution characteristics. Hence, this becomes useful in analyzing the discontinuous and time varying signals especially in islanding detection scenarios.

In addition to this, the WT has three useful characteristics which make it useful in electrical and electronics engineering applications. These include;

- It has the ability to reconstruct back the original signal from its wavelet transform. This is achieved due to wavelet transform's ability of the resolution of identity, the energy conservation in the time-scale space and the wavelet admissible condition.
- Secondly, the WT is a good local operator in both time and frequency domains. Hence, the regularity condition is usually imposed on the wavelets.
- Lastly, the WT has a property related to a multi-resolution signal analysis. Hence, it can be used to analyze both high and low frequency signals. The high frequency signal analysis is done using narrow windows and the low frequency analysis is done using wide windows [43].

Recently, the wavelet transform has been successfully implemented in solving many power system problems including fault detection, power quality event localization and load disaggregation. The capability of wavelet in handling non-stationary signals while maintaining both time and frequency information makes it a suitable candidate for islanding detection problem.

2.5.1 Stationary and Non-Stationary Signals

Signals can be generally classified as either stationary or non-stationary. When the signal characteristics do not change over time, the signal is described as stationary. On the other hand, when the characteristics of a signal are dynamic in nature (i.e. time varying), the signal becomes non-stationary and hence specialized tools for signal analysis are needed to facilitate in extracting the temporal and spectral components of interest in the signal under consideration. The characteristics of non-stationary signals are dynamic in nature making the processing of non-stationary signals challenging [44].

2.5.2 Non-Stationary Signals in Power Systems

There is always transient component in power systems both in voltage and current waveforms following a sudden change in the power system. For instance, when switching of a load, fault inception, opening of breaker, among others. In general, the time and frequency characteristics of voltage and current transient signals are evolving with time in an unpredictable way. In power systems, the root mean square (RMS) index is commonly used to assess the time characteristics (such as time variation trend) of a signal while Fast Fourier transform (FFT) is used to obtain the frequency characteristics (such as harmonic distortion). Wavelet analysis can be categorized into two main techniques. That is; Continuous wavelet transform and discrete wavelet transform.

2.5.3 Continuous Wavelet Transform

The Continuous Wavelet Transform (CWT) is defined in simple terms as the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet function [45]. The time-scale information provided by these wavelets makes it easy to extract signal features that continuously change with time. Mathematically CWT can be expressed as follows;

$$CWT_x^{\emptyset}(a,b) = \frac{1}{\sqrt{a}} \int_{t=-\infty}^{t=\infty} x(t).\emptyset_{a,b}(t)dt \qquad 2.8$$

Where:

a is the scale,

b is the translation or position,

x (t) is the analyzed signal, and

$\emptyset$ is the mother wavelet and is defined by:

$$\emptyset_{a,b}(t) = \frac{1}{\sqrt{a}} \frac{(t-b)}{a} \qquad 2.9$$

The CWT is also continuous in terms of the shift b during the computation process; the wavelet that is used for analyzing the said signal is smoothly shifted over the entire domain of the signal that is being analyzed. It is basically the determination of how similar the considered wavelet is to the original signal through the coefficient calculation. Thus, practically CWT may give redundant information especially when the measured similarity coefficient is large as compared to the original signal [45]. Thus, for the sake of computation, there is need to discretize the signal.

2.5.4 Discrete Wavelet Transform

A discrete wavelet transform (DWT) is any wavelet transform for which the wavelets are sampled at specified intervals. As it is with other wavelet transforms, the main advantage it has over Fourier transforms is that it has the temporal resolution ability. It is able to extract both frequency and location information from the signal in time [46]. The current and voltage transient functions of a power system usually have unique characteristics which can be used to give the cause of a particular transient occurrence [47].

The method used here is based on the fact that transient condition has some given characteristics which can help in presenting a new technique to distinguish the islanding occurrences from the other situations. Of course, the features that are presented in these transient signals cannot be directly interpreted. So, there should be a process to extract these features to speed up response in classifying. To this end, wavelet transform is the most suitable and applicable.

In simple terms, the DWT means the continuous wavelets with the discrete scale and translation factors [48]. The wavelet transform is then determined at certain scales and intervals. Hence, when time localization of the signal is needed, the DWT is the one appropriate. This is especially in islanding detection. The DWT function can be defined as:

$$\emptyset_{a,b}(nt) = |a|^{-\frac{1}{2}}\emptyset\frac{(a-b)}{a} \quad a,b \in R, a \neq 0 \qquad 2.10$$

If (a, b) take discrete value in R, we get DWT. A popular approach to select (a, b) is

$$a = \frac{1}{a_0^m} \qquad a_0 = 2 \ \rightarrow \ a = 1, \frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \dots\dots..m: integer \qquad 2.11$$

$$b = \frac{nb_0}{a_0^m} \qquad a_0 = 2 \qquad b_0 = 1 \qquad b = \frac{n}{2^m} \dots\dots\dots\dots\dots\dots..n, m: integer \qquad 2.12$$

Then

$$\emptyset_{a,b}(nt) = |a|^{-\frac{1}{2}}\emptyset\frac{(t-b)}{a} = 2^{\frac{m}{s}}\left(\frac{t-\frac{n}{2^m}}{\frac{1}{2^m}}\right) = \emptyset_{a,b}(t) = 2^{\frac{m}{2}}\emptyset(2^m t - n) \qquad 2.13$$

A lower level of decomposition for the signal should be taken for the response time of the islanding detection algorithm to be shorter.

2.5.4.1 The merits of DWT

Discrete wavelet transform (DWT) has a number of strong points which makes it suitable in islanding detection. These include;

- Its ability to sufficiently provide enough information both for synthesis and analysis purposes
- It drastically reduces the computation time of the signal
- Easiness to implement
- Its ability to analyze signals at different frequency bands with different resolutions
- Its ability to decompose signals into coarse approximation (CA) and detail information (DI)

2.5.4.2 Limitations of DWT

Although the DWT is usually a very powerful tool in signal analysis, it has two major disadvantages that undermine its application for certain signal and image processing tasks.

- Unavailability of shift invariance. This is as a result of the down-sampling operation at each signal level. That is why if the input signal is changed slightly, the amplitudes of the corresponding wavelets coefficient varies drastically.
- Absence of the directional selectivity. Here, the given DWT filters are real and separable. Hence, they cannot distinguish between the opposing diagonal directions of the signals being analyzed.

The merits of DWT supersede its demerits by far. Its main application here is in the extraction of signals quickly and easily and then decomposes it into Coarse Approximation (CA) and Detail Information (DI) which is used in both synthesis and analysis purposes. However, its lack of shift invariance and lack of directional selectivity, which appears as weaknesses, is not a major problem when analyzing discontinuous signals in islanding detection. The comparison of these merits and demerits comes in play depending on where this is applied.

Associated with the wavelet transform is a scaling function $\emptyset(t)$. This scaling function along with the wavelet function makes a Multi-Resolution Analysis (MRA) characteristic of the signal being analyzed. The scaling function of one level can be represented as a sum of a scaling function of the next finer level as shown by equation 2.14

$$\emptyset(t) = \sum_{n=-\infty}^{n=\infty} h(n)\sqrt{2}\emptyset(2t - n) \qquad 2.14$$

The wavelet function is also related to the scaling function by equation 2.15

$$\varphi = \sum_{n=-\infty}^{n=\infty} h_1(n)\sqrt{2}\emptyset(2t - n) \qquad 2.15$$

Where $h(k)$ and $h_1(k)$ represent the scaling and wavelet functions, respectively, and are related as

$$h_1(k) = (-1)^k h(1 - k) \qquad 2.16$$

The three level wavelet decomposition structures are given in Figure 2.11

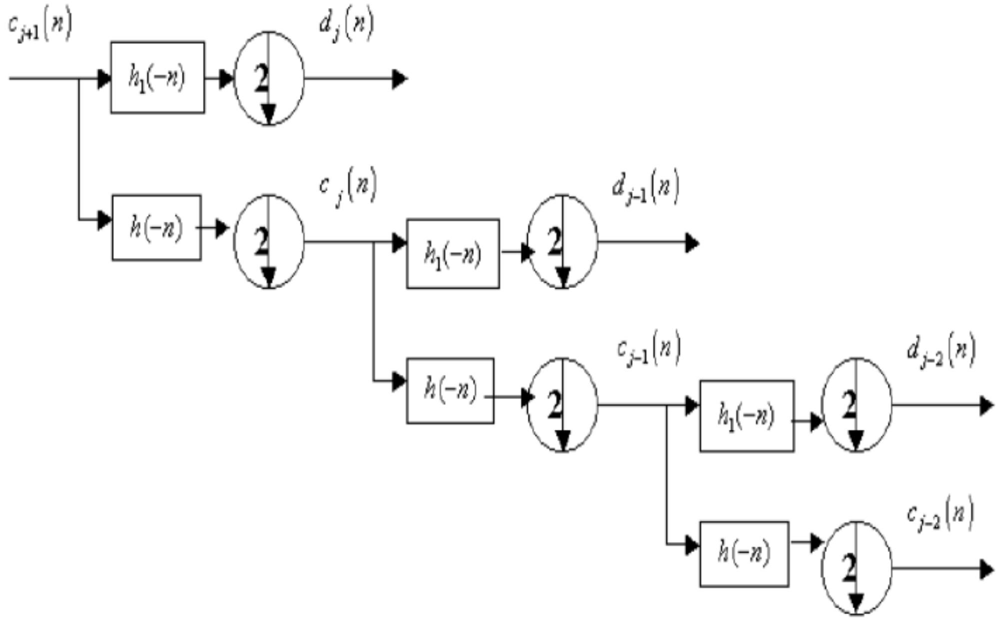

Figure 2.11: Three level wavelet decomposition

2.6 Fuzzy Logic Controller

A fuzzy logic controller is a control algorithm based on several linguistic control rules connected along them through a fuzzy implication and a compositional rule of interference, together with a defuzzification mechanism. That is, a mechanism that changes the action of fuzzy control into one which is not fuzzy [49]. Also, the fuzzy rule base can handle more uncertainties (like noise), which falls on the slope of the fuzzy trapezoidal membership functions. This as opposed to the crisp classifiers such as decision tree having sharp boundaries, with a larger data base. Thus, the superior approximation capabilities of the fuzzy systems over crisp classifiers help to develop the relay to meet the real-time application with wide range of uncertainties [50].

2.7 Performance Assessment of Islanding Detection Methods for SDGs

Earlier studies have already proposed graphical measurement tools to assess the performance characteristics of the protection relays for distributed generation [51] [52]. The Islanding Detection Methods (IDMs) can also be evaluated graphically, using Non-Detection Zones (NDZs) and performance curves (PCs). Thus, it is possible not only to identify the main limiting factors that affect the performance of the evaluated IDM, but also to optimize the setting of the anti-islanding protection parameters [19].

2.7.1 The Non-Detection Zones

By definition, a Non-Detection Zone (NDZ) represents an interval in which the islanding detection scheme fails to detect islanding condition once it has occurred [53]. Most passive islanding detection algorithms suffer from large NDZs. The NDZ can be calculated in terms of the power difference space (ΔP and ΔQ) or using the load parameter spacing. The load type, generator inertia constant, generator excitation control mode and relay settings are some of the factors that affect NDZs for synchronous generators. This is shown in figure 2.12 [19].

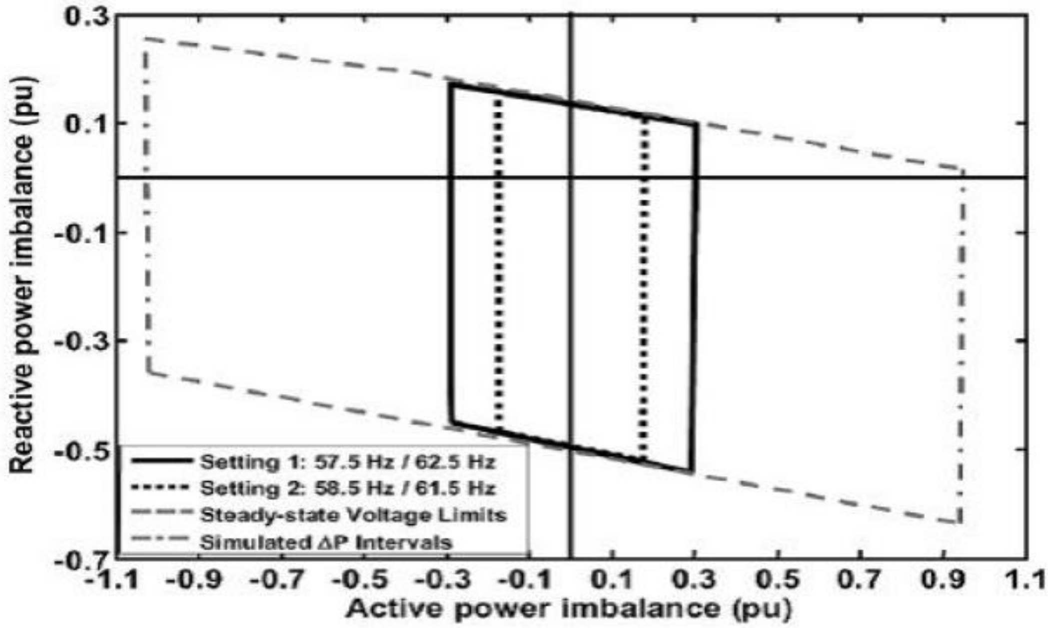

Figure 2.12: NDZs for different frequency relay settings

2.7.2 Islanding Detection Performance Curves

Performance Curves (PCs) represent the relationship between the islanding detection times against the active power difference. This graphical tool is especially useful for synchronous DGs. Power mismatches lower than the critical power imbalance make up a NDZ. This is illustrated in Figure 2.13 [19].

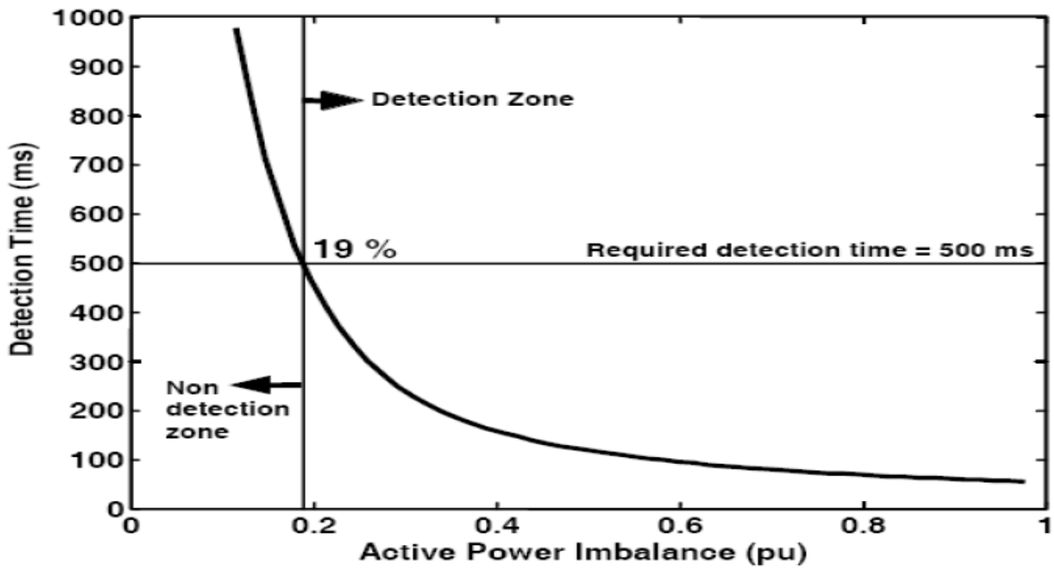

Figure 2.13: Frequency relays performance curve

2.8 ARTIFICIAL BEE COLONY ALGORITHM

2.8.1 The Nature of Bees

The Swarm Intelligence (SI) is a branch of Artificial Intelligence (AI) that has its basis on the collective characteristics of animals or certain unique phenomenon of natural setups such as bees, fish, ants and birds. In the process of searching for the food sources, the bee colony can move in several directions and over a distance of several kilometers.

This exercise of searching for new food sources starts by sending out a group of scout bees to search for flower patches at various bushes that contain a considerable amount of nectar and pollen. After this, the scout bees come back to their hive and then perform a special movement as others observe. This dance is known as the waggle dance. This is shown in figure 2.14. This waggle dance is used by the employed bees to communicate to other bees in the hive to report three main types of information. This is with regards to the availability of flower patches, which are the direction of food sources location, their quality, quantity and distances from these food sources [54].

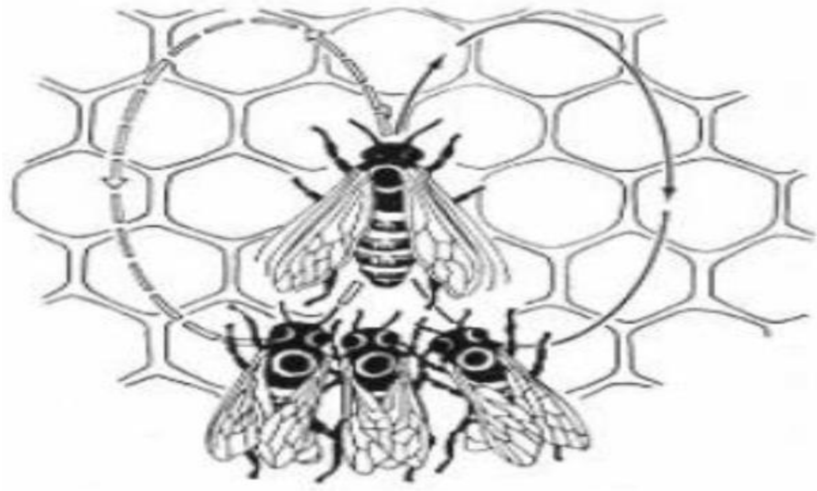

Figure 2.14: The bees waggle dance

This information conveyed helps the other bees in the hive to travel towards the discovered flower patches more easily and precisely without the assistance from other bees. After the waggle dance, scout bees will fly back to the flower patches again with follower bees or worker bees [55].

The artificial bee colony algorithm consists of three important components in its operation. That includes the employed bees, unemployed foraging bees, and food sources.

- Food Sources: An artificial bee analyses a number of factors concerning a given food source before selecting it. These factors include the closeness of the food source to the hive, richness and quality of the energy, taste of its nectar, and the ease or difficulty of extracting this food from the source.
- Employed bees: An employed artificial bee is often employed at one certain food source at a time which she exploits. She carries all important information about this particular food source and shares it with the rest of the bees waiting in the hive. Among other information she shares include the distance of the food source from the hive, its direction and how profitable it is.
- Unemployed bees: Group forager bees that are looking for food sources to exploit are called unemployed bees. They can be either scout bees that search

around the environment randomly or onlooker bees who try to find food sources by using the information given by the employed bees. The mean number of scouts is about twenty percent.

In short, the artificial foraging bees consist of a group of employed bees, onlookers and scout bees. Half of this colony comprise of the employed bees which forms the majority.

Every food source has an employed bee associated with it. Once a food source is depleted, the employed bee automatically becomes a scout. Thus, the amount of nectar in a batch of flowers determines the fitness value of that solution, in this case the food position.

The basic mechanism search of ABC is well presented in figure 2.15 [56] where (a) is the Initial situation and (b) is the Final situation.

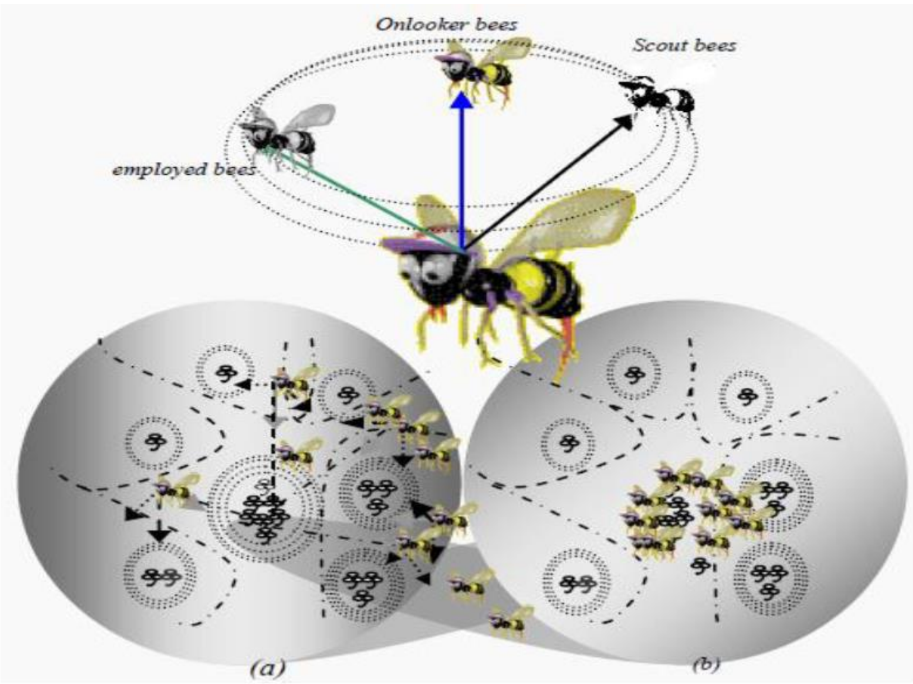

Figure 2.15: Basic mechanism search of ABC

In the initialization stage of the ABC algorithm, it creates a randomly distributed initial population of solutions (*f = 1, 2... Eb*), where *f* signifies the size of population and *Eb* is the number of employed bees [28]. Each solution of the expression *xf* is a *D* dimensional size vector, where *D* is the optimization parameters number. Throughout the optimization process, the artificial bees will memorize the new food position, that is, the modified solution, if the quantity of the new nectar position is higher than the previous nectar position.

Upon completion of each of the search process, the bees then share the nectar information they have found with onlooker bees in the beehive dance area. The onlooker bee will carefully observe these waggle dances and evaluate the information being conveyed and choose the food source with highest nectar quantity. The onlooker bees evaluate the nectar information and choose a food source depending on the probability value associated with that food source using the equation 2.17 below [57];

$$P_i = \frac{fit_i}{\sum_{j=1}^{ne} fit_j} \qquad 2.17$$

Where fit_i is the solution's fitness value *i*, which in turn is proportional to the amount of nectar of the source of food in the position *i* and *ne* is the number of food sources which is equal to the number of employed bees in the colony [52].

On their turn, the onlooker bees also employ the same process of modification and selection of the food positions as the employed bees do. This can be demonstrated by the equation 3.2.

$$v_{ij} = x_{ij} + Q_{ij}(x_{ij} - x_{kj}) \qquad 2.18$$

Where $k \in (1,2...ne)$ and $j \in (1, 2....D)$ are selected randomly. Although *k* is determined stochastically, it should not be equal to the value of *i*. $\emptyset_{ij}$ is a random number which should be between -1 and, 1. This controls the generation of the neighborhood food sources.

When the food-source position has been abandoned, the employed bee associated with it becomes a scout. The scout produces a completely new food source position as using this equation; $v_{ij} = x_{ij} + Q_{ij}(x_{ij} - x_{kj})$.

Once the new food position is determined as shown above, another cycle of the ABC algorithm begins. The same procedures are continuously repeated until the stopping criterion is met [28]. In nutshell, the ABC algorithm is a cycle which involve the following steps which are repeated until the stopping criteria is achieved [58];

Initialization Phase

REPEAT

- Employed foragers Phase
- Onlooker foragers Phase
- Scout foragers Phase
- Memorization of the best food solution achieved

UNTIL (Cycle = Maximum number of Cycles)

Generally, the ABC algorithm steps can be summarized as shown in figure 2.16 [10]:

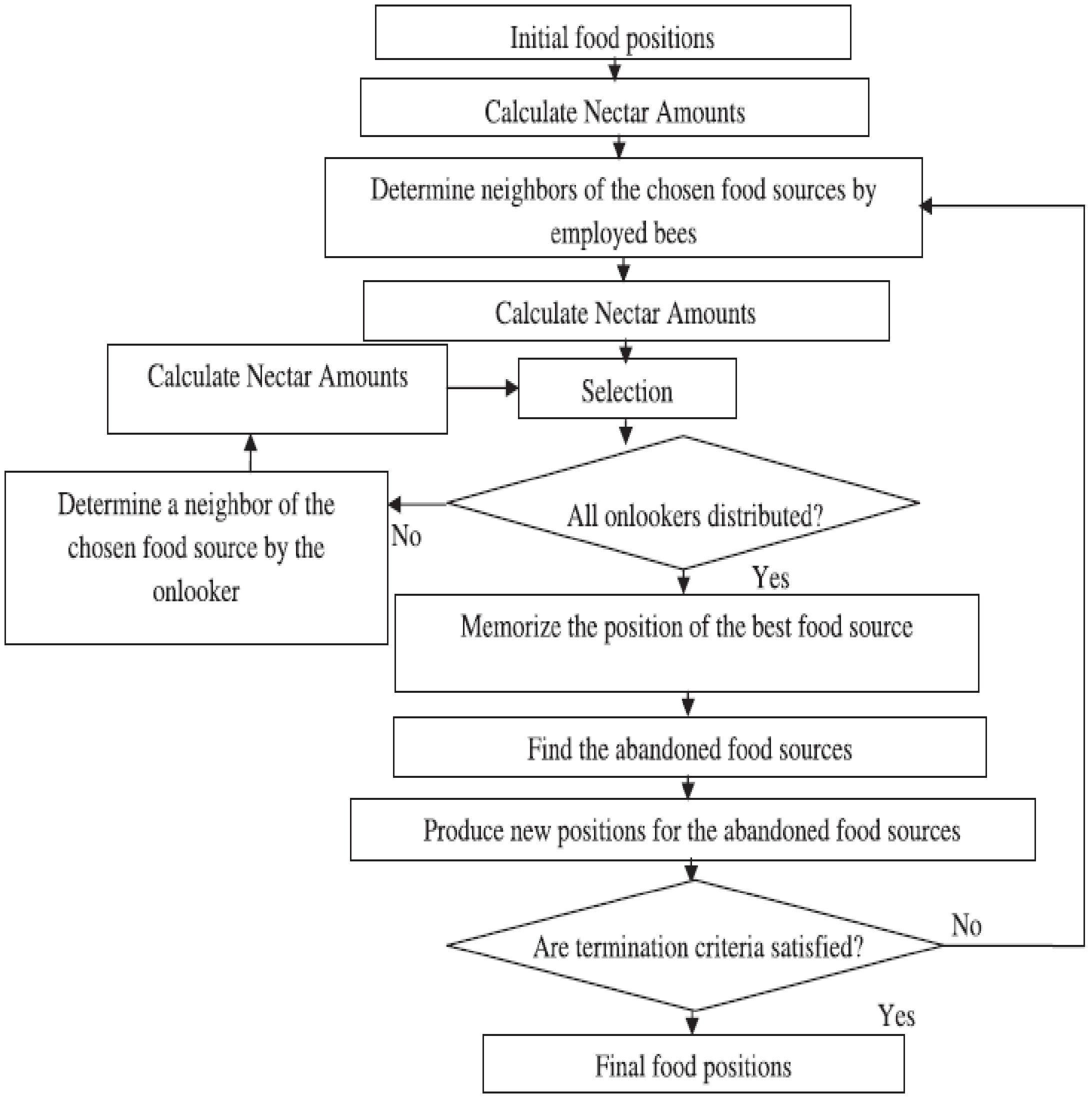

Figure 2.16: Artificial bee colony algorithm flow chart

The general ABC algorithm steps, as shown in the figure above, in relation to islanding detection can be explained as follows:

Step 1 Initialize the food-source positions x_f (solutions population), where $f = 1 \ldots Eb$. The x_f solution form is as follows.

Step 2 Calculate the nectar amount of the population by means of their fitness values using $fitness = \frac{1}{1 + power\ loss}$

Step 3 Produce neighbor solutions for the employed bees by using $v_{ij} = x_{ij} + Q_{ij}(x_{ij} - x_{kj})$ and evaluate them as indicated by Step 2.

Step 4 Apply the greedy selection process.

Step 5 If all onlooker bees are distributed, go to Step 9. Otherwise, go to the next step.

Step 6 Calculate the probability values for the solutions *xf* using $P_i = \frac{fit_i}{\sum_{j=1}^{ne} fit_j}$.

Step 7 Produce neighbor solutions for the selected onlooker bee, depending on the value, using $fitness = \frac{1}{1+power\ loss}$ and evaluate them as Step 2 indicates.

Step 8 Follow Step 4.

Step 9 Determine the abandoned solution for the scout bees, if it exists, and replace it with a completely new solution using $v_{ij} = x_{ij} + Q_{ij}(x_{ij} - x_{kj})$ and evaluate them as indicated in Step 2.

Step 10 Memorize the best solution attained so far.

Step 11 If cycle = MCN, stop and print result. Otherwise follow Step 3.

2.8.2 Advantages of ABC algorithm

The artificial bee colony algorithm system combines both the local search which is carried out by the employed and onlooker groups of bees, and also the global search which is managed by the onlookers and scout group of bees which attempts to balance the exploration and exploitation process [59]. The main advantages of the ABC algorithm over other optimization methods for solving optimization are [60] [61] [62] [63]:

- It is simple to deploy
- It is highly flexible
- It is robust
- It has few control parameters
- Its ease of combination with other methods
- Its ability to handle the objective with stochastic nature

- Its fast convergence as it combines both exploration and exploitation processes.

2.8.3 Disadvantages of Artificial Bee colony algorithm

The artificial bee colony algorithm has some few weaknesses when put into practice.

- First this method requires new fitness tests on every new algorithm parameters so as to improve performance
- It needs a high number of objective function evaluations
- It slows down when used in sequential processing and the population of solutions increases the computational cost due to slowdown
- It has many iterations and thus huge memory capacity required.

CHAPTER THREE

METHODOLOGY

In order to achieve the objectives outlined above, this study was broken down into two sections. Part one are the procedures for islanding condition detection using DWT and FL. The second part deals with power prioritization and optimization within the island using ABC algorithm. This is elaborated as follows:

3.1 Simulation Model

The system block diagram that was used for simulation in this study is as shown in the figure 3.1 and its corresponding MATLAB/SIMULINK model is shown in figure 3.2. This system comprises a single rotating machine based DG and the main grid interconnected at the PCC. The features are extracted by DWT and then classified by FL as islanded or not islanded. This scheme monitors the status of the system continuously so as to ensure an island does not occur and remain undetected.

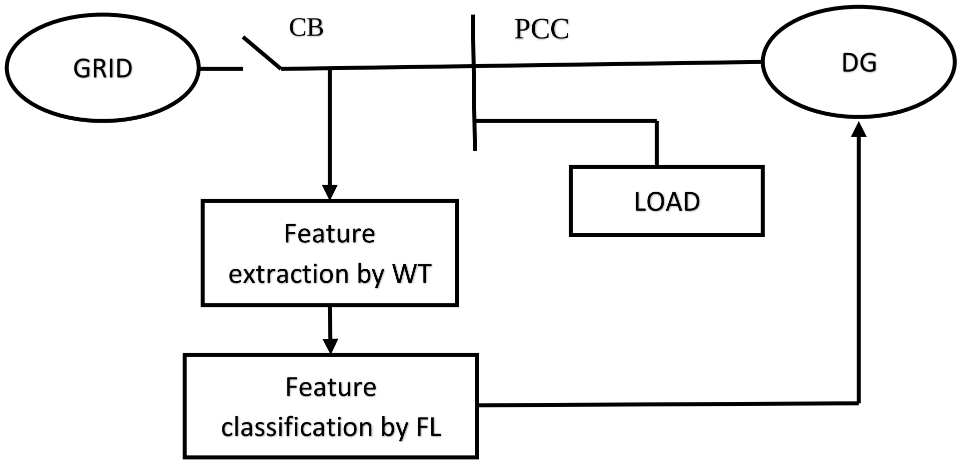

Figure 3.1: Simulation model for this study

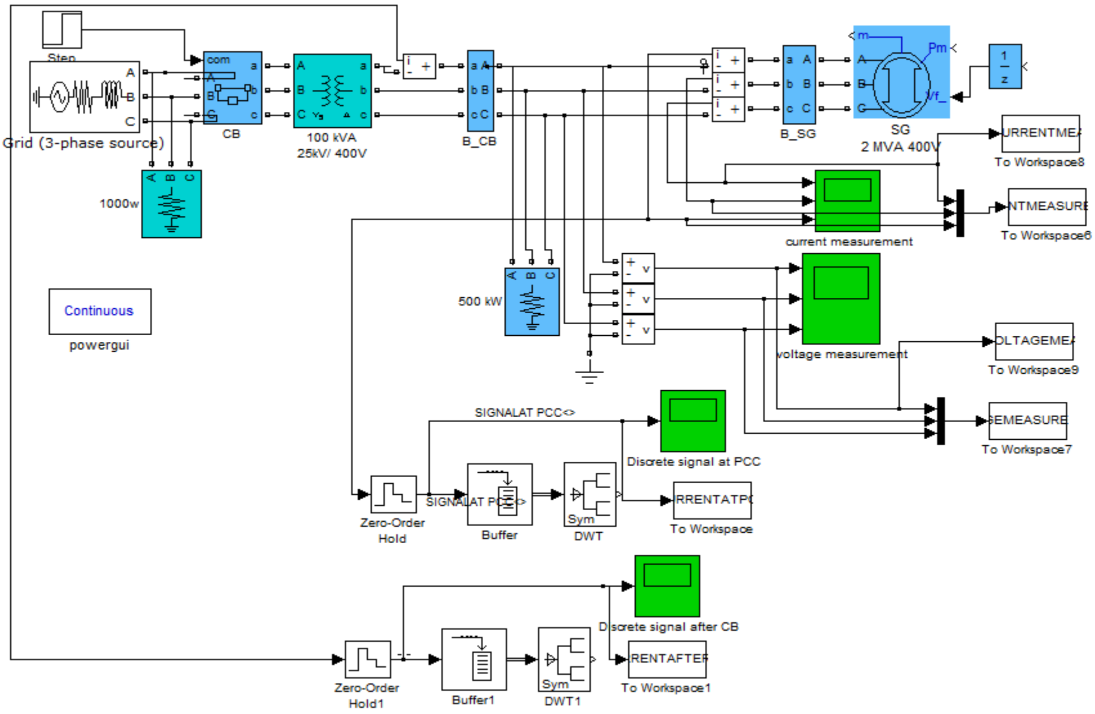

Figure 3.2: Model in Simulink

The 500W shunt resistance load is used to absorb power proportional to the square of the applied voltage at a certain frequency hence regulating the excitation output to the required levels. The power factor of this load is 0.9 lagging.

3.2 System parameters

The system parameters for this study were then set as follows;

i. Load data: Nominal ph-ph voltage: 400 Vrms, Nominal frequency: 50 HZ, Active power: 500KW, Configuration: Y(grounded)
ii. Synchronous machine (Generator) data: Rotor type: salient pole, Nominal power: 2MVA, Voltage: 400Vrms, Frequency: 50HZ, field current: 100A
iii. Transformer data: 25kV/400V, 100kVA, Frequency: 50HZ
iv. Grid data: Phase to phase rms voltage: 25KV, Frequency: 50HZ, Internal connection: Yg, 3-phase short circuit level at base voltage: 100mva

3.3 Feature Extraction

Then the position of measuring the signal frequency was changed to immediately after the utility circuit breaker from the usual Point of Common Coupling (PCC). This changing of the point of signal sampling is meant to make frequency measurement fast and ensure the island detection time is even less than what is stipulated by IEEE 1547-2003 standard of two seconds. On the other hand, the signals were also taken from the PCC and then compared. Note that this islanding detection time is the same irrespective of the system frequency under consideration, that's either 50 Hz or 60Hz power system. This is evidenced by the paper presented in the International Conference on renewable Energies and Power Quality, by A. Etxegarai, I. Zamora, P. Egui and L. Valverde titled "Islanding Detection of Synchronous Distributed Generators". This paper in based on the IEEE 1547-2003 standard and their model for analysis was done on a 50Hz system [18].

During simulation, the grid was disconnected on the 2s by switching off the three-phase circuit breaker thus isolating the DG from the main grid. Then the features of the measured frequency were extracted by Discrete Wavelet Transform (DWT), a tool found in MATLAB toolbox.

These features are extracted under different islanding and non-islanding conditions of the network. That is, when the circuit breaker (CB) is both closed and also tripping it to create the condition of islanding of the distributed generator while supplying the bus loads at the PCC. The extracted features are then subjected to fuzzy logic algorithm as shown in the figure 3.3 to determine the islanding and non-islanding condition.

3.4 Feature Classification

The extracted frequency features were subjected to artificial intelligence classifier, in this case fuzzy logic (FL) to classify the signal as islanding or not islanding. The fuzzy logic was chosen because it can handle more uncertainties (like noise), which falls on the slope of the fuzzy trapezoidal membership functions, compared to the crisp classifiers such as decision tree having sharp boundaries, with a larger data base. This is shown in figure 3.3

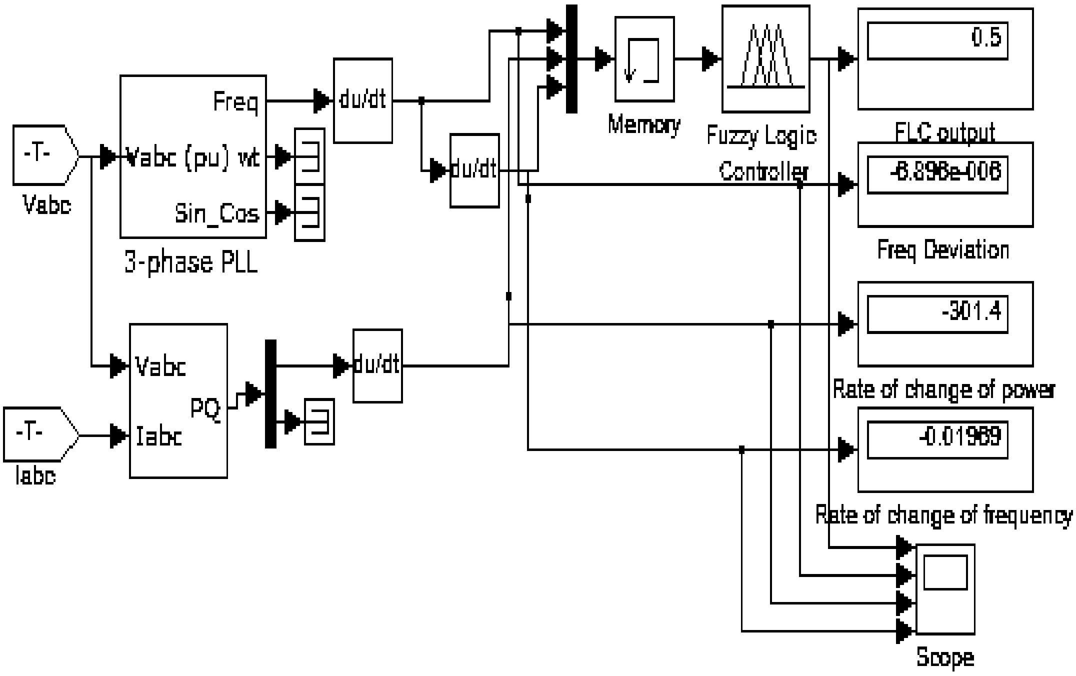

Figure 3.3:Fuzzy inference system for islanding detection

In this system, the following three main features are chosen, measured and then be used in the algorithm. These include Frequency Deviation, Rate of Change of Power (ROCOP) and Rate of Change of Frequency (ROCOF). However, under normal circumstances, there are eleven features that can be measured and used in islanding detection. Among all these features, only the three mentioned above are sufficient in islanding detection.

3.4.1 Frequency Deviation

Frequency deviation in power system is depended on the power imbalance. This imbalance in active power causes transients when the island occurs and the loads in that section are solely supplied by the DG. Hence the DG frequency increases or decreases. This makes the frequency deviation one of the best approaches when it comes to islanding condition detection. The phase–locked loop (PLL) block is used here to achieve the frequency waveform that is used in this analysis.

3.4.2 Rate of Change of Power

The Rate of Change of Power (ROCOP) is used here to check the effect that active power variations have on the frequency and voltage in the system. The impact of this ROCOP is negligible and insignificant when the DG is in parallel connection with the mains. However, its impact become significant when the DG is islanded. This is also not affected with small local load changes and during system fault conditions.

3.4.3 Rate of Change of Frequency

Rate of Change of Frequency (ROCOF) is used to give the relationship between the frequency and the active power flow in the system. This is more stable when the DG is operating in parallel with the grid as compared to when it operating in an island.

3.5 DG Field connections

The generator field current and voltage was observed throughout this analysis and it characteristic captured. From the principle of operation of SDGs, a direct current (DC) is normally applied to the windings of the rotor so as to produce the magnetic field at the rotor. Figure 3.4 below is the circuit used to generate the field signals.

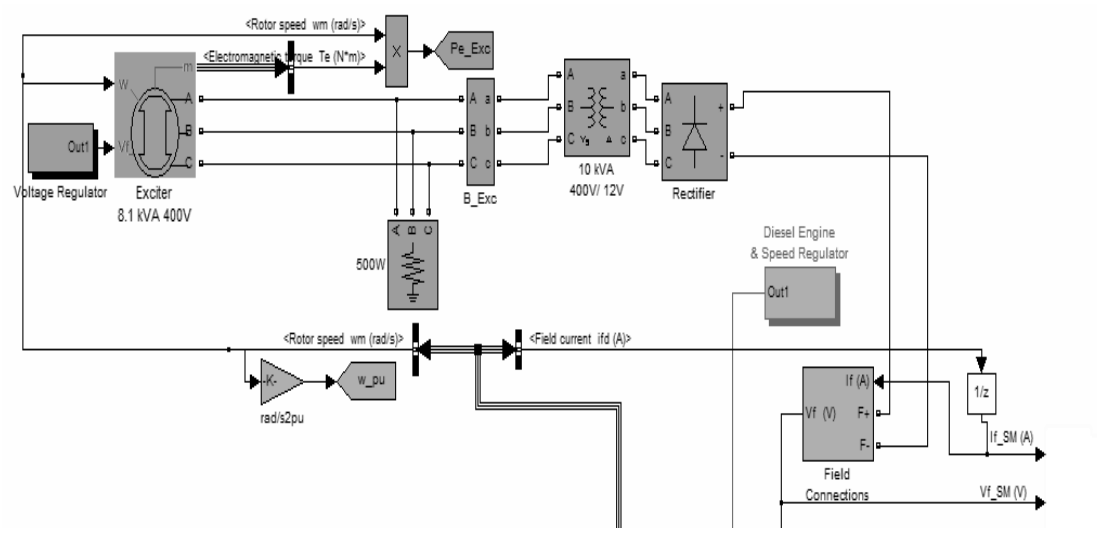

Figure 3.4: DG Field connections

3.6 Power Prioritization

The last part of this study was to determine the minimum load amount for shedding within the islanded region so that we can maximize the electricity supply to customers in case the load surpasses the supply within that island. To achieve this, artificial bee colony (ABC) algorithm was used to ensure there is optimum power supply and also perform power prioritization to determine the buses to be shed based on their priority index.

The IEEE fourteen bus was used in the analysis but with little modification on the bus data and line data. To start with, the distributed generator of 320MW was connected at bus number two and a number of loads connected at different buses totaling to 362MW. Then these parameters were varied separately while keeping the other constant and observations made. The control parameters of ABC algorithm are assumed as follows:

- The number of colony size is assumed to be twenty. This represents the number of possible solutions in islanding detection.
- The fitness value of the food source equals to the sources of food. This value is half the colony size.
- The limit of iteration is taken to be a hundred in this case. This means any food source that cannot improve after this limit shall be abandoned.
- Finally, the foraging number is also taken as a hundred.

3.6.1 ABC Parameters in Relation to System in study

The ABC system combines local search methods, carried out by employed and onlooker bees, with global search methods, carried out by the onlookers and scouts, which try to balance the processes of exploration and exploitation.

- Here, a food source stands for a potential solution of the problem to be optimized. The ABC algorithm is an iterative algorithm, starting by associating all employed bees with randomly generated food solutions. It is actually any number of buses that can be shed from the system for optimization purposes.

- The acronym *SN* is the number of food sources which is equal to the number of the onlooker and employed bees in the hive.

- The parameters to be optimized is represented by *D*.
- The acronym fit_i in the equation $P_i = \frac{fit_i}{\sum_{j=1}^{ne} fit_j}$ is the fitness value of the i^{th} solution evaluated by the employed bee. Obviously, when the maximum value of the food source decreases, the probability with the preferred source of an onlooker bee decreases proportionally. This is used in determining which buses that should not be shed based on the priority index placed on them and which ones that can be shed incase supply is less than load demand in that island.
- If a given food source does not improve after a certain number of the trails, that food source should be abandoned. The employed bees associated with that source will become scout bee and then will randomly search for another source of food using the equation: $v_{ij} = x_{ij} + Q_{ij}(x_{ij} - x_{kj})$. In this system, ABC algorithm uses this to move to the next bus for evaluation after making a decision to shed the previous bus due to its low priority index attached to it.

After the new source is produced (bus to shed), another iteration of the ABC algorithm will begin. The whole process repeats again till the termination condition is met.

3.6.2 IEEE 14-bus system

This system consists of five synchronous machines, including one synchronous compensator used only for reactive power support and four generators located at buses 1, 2, 6, and 8. In the system, there are twenty branches, fourteen buses and with 11 loads connected. Table 3.1 and 3.2 below shows the 14 bus and line data with the modifications that was used in this study.

Table 3.1: IEEE 14-bus data

Bus	Type	Vsp	theta	PGi	QGi	PLi	QLi	Qmin	Qmax
[1	1	1.0	0	0	0	0	0	0	0
2	2	1.0	0	300	0	21.7	0	0	0
3	3	1.0	0	0	0	94.2	0	0	0
4	3	1.0	0	0	0	47.8	0	0	0
5	3	1.0	0	0	0	7.6	0	0	0
6	3	1.0	0	0	0	11.2	0	0	0
7	3	1.0	0	0	0	0.0	0	0	0
8	3	1.0	0	0	0	0.0	0	0	0
9	3	1.0	0	0	0	30	0	0	0
10	3	1.0	0	0	0	30	0	0	0
11	3	1.0	0	0	0	30	0	0	0
12	3	1.0	0	0	0	30	0	0	0
13	3	1.0	0	0	0	30	0	0	0
14	3	1.0	0	0	0	30	0	0	0

Table 3.2: IEEE 14-bus line data

From Bus	To Bus	R pu	X pu	B/2 pu	X'mer TAP (a)
[1	2	0.01938	0.05917	0.0264	1
1	5	0.05403	0.22304	0.0246	1
2	3	0.04699	0.19797	0.0219	1
2	4	0.05811	0.17632	0.0170	1
2	5	0.05695	0.17388	0.0173	1
3	4	0.06701	0.17103	0.0064	1
4	5	0.01335	0.04211	0.0	1
4	7	0.0	0.20912	0.0	0.978
4	9	0.0	0.55618	0.0	0.969
5	6	0.0	0.25202	0.0	0.932
6	11	0.09498	0.19890	0.0	1
6	12	0.12291	0.25581	0.0	1
6	13	0.06615	0.13027	0.0	1
7	8	0.0	0.17615	0.0	1
7	9	0.0	0.11001	0.0	1
9	10	0.03181	0.08450	0.0	1
9	14	0.12711	0.27038	0.0	1
10	11	0.08205	0.19207	0.0	1
12	13	0.22092	0.19988	0.0	1
13	14	0.17093	0.34802	0.0	1];

3.6.3 Overall System Flow Chart

First, the frequency signals are sampled from the power line. In this study, current signals only were sampled and used in the analysis. Then features to be used in islanding detection were extracted by the use of discrete wavelet transform and the classification was done using fuzzy logic as either islanded or not islanded. In case of islanded condition, power optimization and prioritization was done within the island using ABC algorithm. Generally, the system flow chart as shown in figure 3.5.

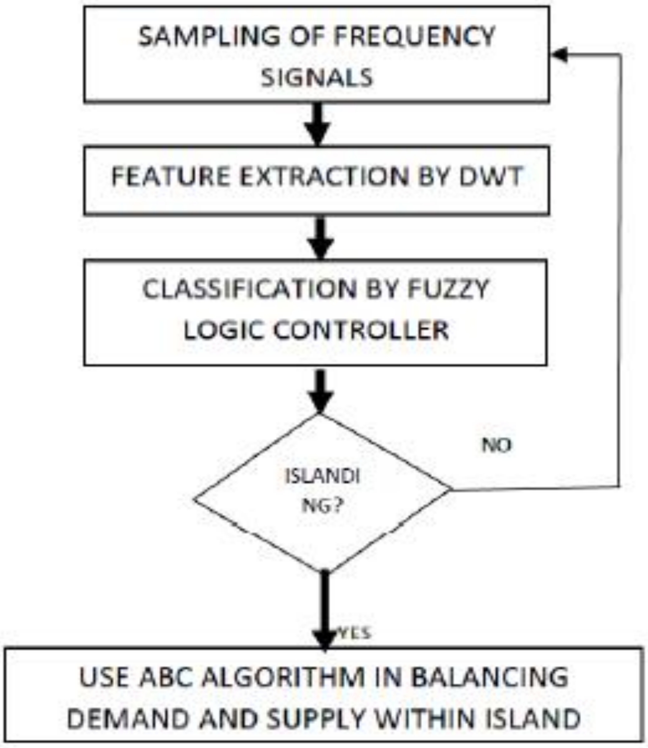

Figure 3.5: System flow chart

The steps of proposed ABC algorithm for power prioritization can be summarized as follows:

1. Set the Artificial Bee Colony control parameters: ie the maximum cycle number (MCN), the optimization parameter number (D) and limit which depends on colony size (SN) and D.
2. The system data should be read.

3. Run the power flow algorithm
4. Food positions *xi* should be initialized, where *i = 1, 2…Eb*
5. Run the power flow for each and every position and confirm whether the voltage limits are within required range.
6. If the voltages are within the required range, then check if all the sources of food are produced, otherwise go to step 4.
7. If all the sources of food are produced, then calculate the fitness values of x*i*. Otherwise go to 4.
8. Change the x_i solutions to give neighbors with equation number 6 above. They should then be evaluated as shown in 5.
9. Make the Comparisons for the food positions before applying selection.
10. If all the onlooker bees are well distributed skip to 13. Otherwise, go to 11.
11. Evaluate the probabilities by using step 5.
12. For the chosen onlooker bees, calculate the neighbor solution using 6.
13. Turn back 9.
14. Take the abandoned algorithm solution and in it put 7. Evaluate the voltage limits and calculate the fitness then go to 15. Otherwise a new solution should be evaluated using 7.
15. Store the next solution *xi*.
16. If cycle=maximum cycle number, then stop and print the solution of *xi*.

CHAPTER FOUR

RESEARCH RESULTS AND DISCUSSION

4.1 Islanding Detection and classification Using DWT and FL

First, the combined three phase voltages and currents were measured and are as shown in the figure 4.1 and figure 4.2. Usually the observation of voltage and current signals is the best way for detection and protection schemes in the electrical power systems.

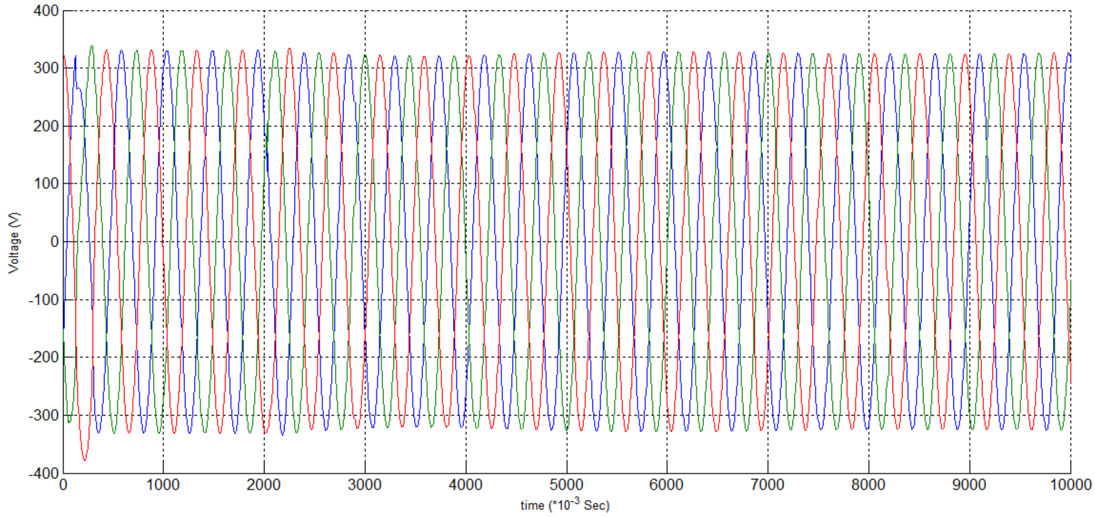

Figure 4.1: Three phase voltage measurement

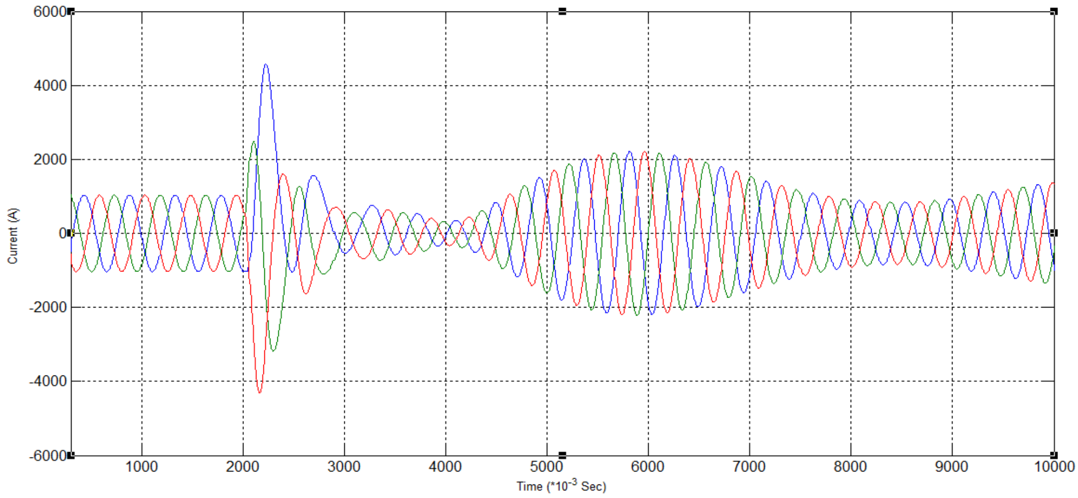

Figure 4.2: Three phase current measurement

As it can be observed from figure 4.1 and figure 4.2, the amplitudes of voltage and current signals change significantly and this can provide the best sign for detection of islanding during islanding operation of the DG. From the figure, it clearly shows that there are more amplitude variations on the side of the measured currents as compared with the measured voltages. Thus, current measurement was mainly used in the rest of the analysis.

Next, the phase voltages and currents were measured separately for the sake of clarity and are as shown in figure 4.3 and figure 4.4. From these measurements, there is remarkable changes in both current and voltage measurements on the 2nd second when the main grid CB was opened to create an island. As it can be observed, the Red, Yellow and Blue phases current measurements are more clear as compared with the Red, Yellow and Blue voltage measurements.

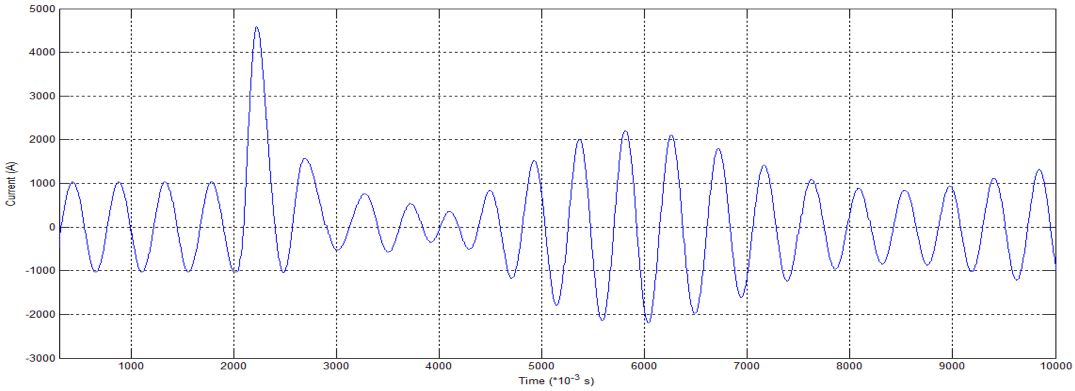

Figure 4.3: Red phase current measurement

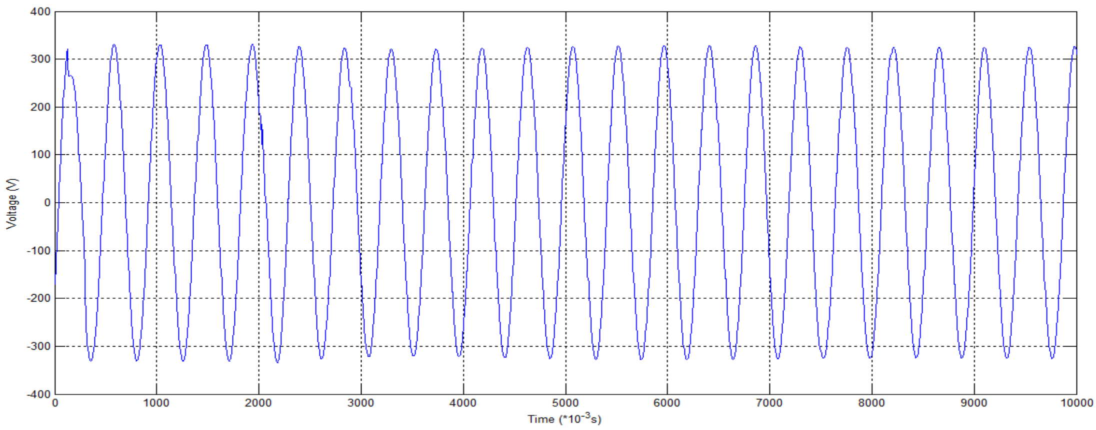

Figure 4.4: Red phase voltage measurement

Then the exciter voltages and current changes during the same time of islanding were monitored and are as shown in figure 4.5 and figure 4.6. As it can be observed from the figure, the excitation currents respond in 0.25 seconds after the fault occurs while the voltages do not have much variations. Though the voltage also changes, it does not vary immediately as the current values does. This is associated with the existence of AVRs in the system among other factors. The function of the AVR is to maintain constant voltage and power line conditioning to the equipment load under a wide variety of conditions, even when the utility input voltage, frequency or system load vary widely. It can also be observed that there are more variations in the excitation current than the variations in the excitation voltage.

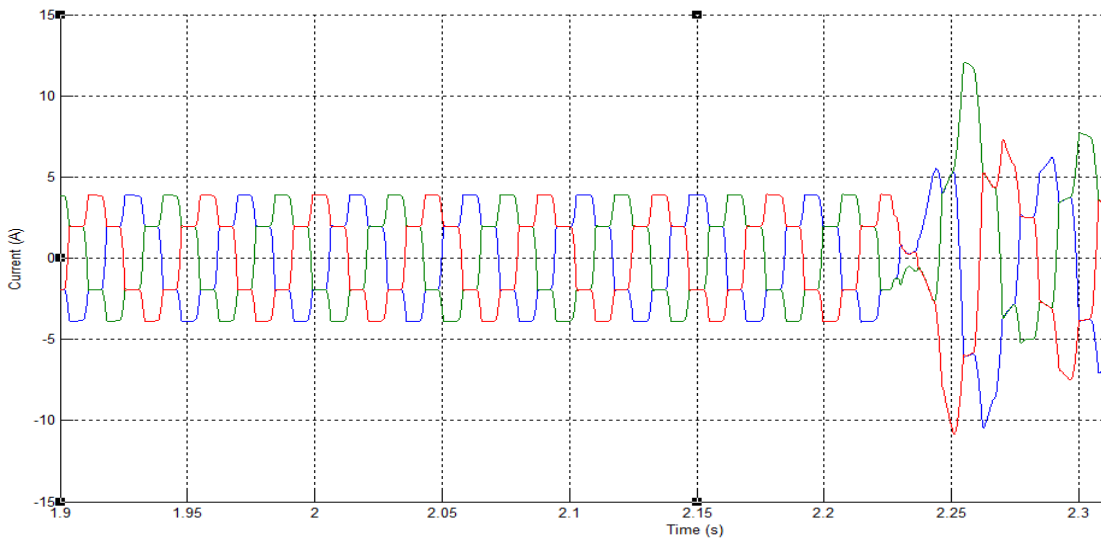

Figure 4.5:Excitation current

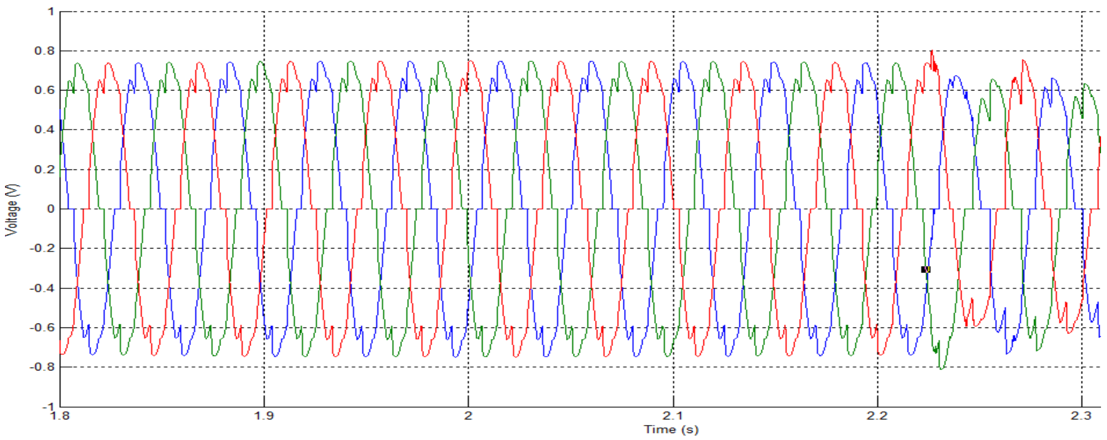

Figure 4.6: Exciter voltage

In practice, large generators make use of brushless exciters in their excitation. The brushless exciters are small AC generators which have their field circuits placed on their stators and their armature circuits positioned on the shafts of the rotors. The outputs from exciters are then rectified and converted to DC before being fed into the main network field circuit.

The current waveforms of one phases at the PCC and just after the utility CB was measured during the same period and is as shown in figure 4.7 and figure 4.8 below.

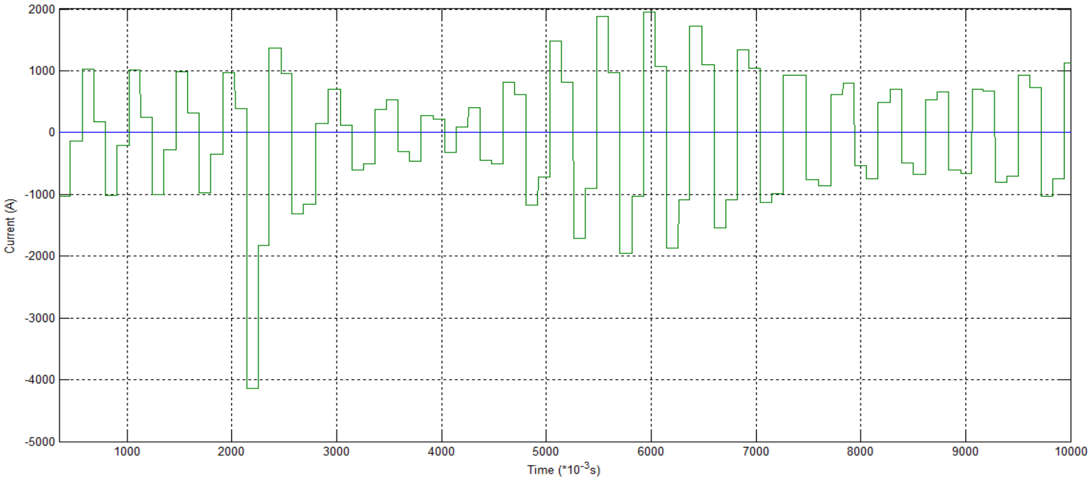

Figure 4.7: Current measurement at the PCC

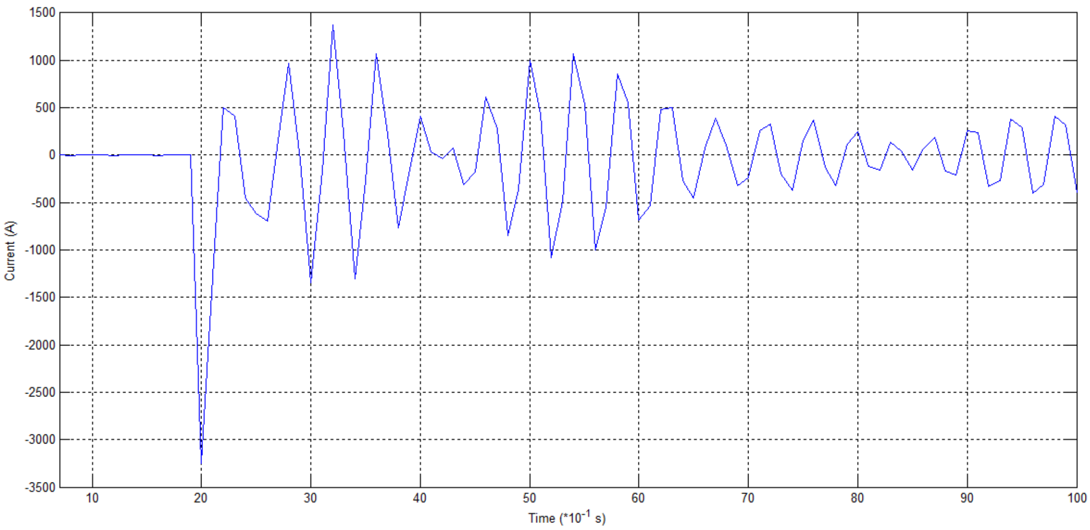

Figure 4.8: Current measurement just after the utility CB

As it can be observed, there is remarkable and more clear signal changes when the measurements are taken just after the utility circuit breaker. Here the current changes immediately from 0-3500A immediately on the 2nd second as the CB is opened to create an island. This is in comparison with the signal taken at the PCC which delays for about 0.2 seconds before the signal amplitude changes to about 4000A. Hence the signal measurement after the PCC will be preferred in islanding detection analysis in this study.

The discretized waveform was then decomposed up to 5 levels and is as shown in figure 4.9. As it can be observed, the measured signal is stable up to 0.2 seconds after the utility CB was opened. Then after this the signal amplitudes changes from 1000A up to 4000A. It can be pointed out from the transform, that the decomposition of the signal to level 2 (D2) is enough in determining the islanding condition in this case.

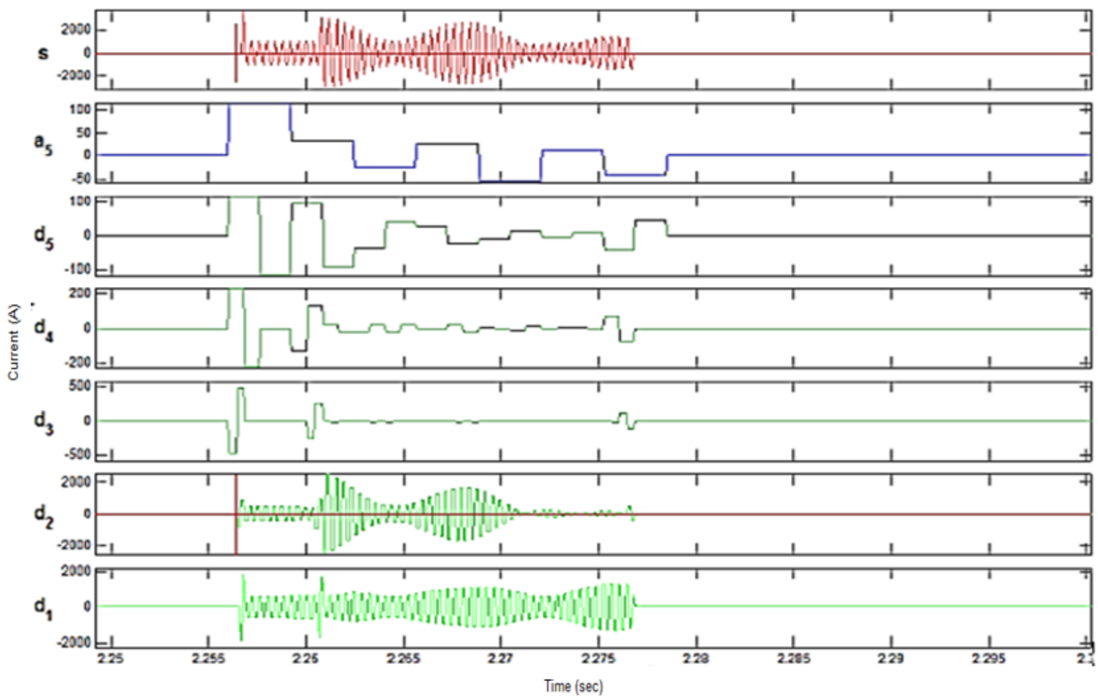

Figure 4.9: DWT for the analysed signal

Thus, the islanding detection time is seen to be smaller, that is 0.26 seconds, when a lower decomposition level is chosen, in this case decomposition to level 2.

Generally, in the literature, most of the work done considering the use of wavelet in islanding detection has shown successful implementation of several wavelet families in solving many problems in field of engineering. Among which, the most commonly used families are: Daubechies, Symlets, and Coiets. The characteristics of each family depend on the following properties:

- The wavelet functions and the scaling associated with it should be orthogonal so as to enable the decomposition of the signal into approximate (A) and detailed (D) sub-bands respectively.
- The wavelet in consideration should have a linear response in its phase that will help to avoid distortion in the process of decomposition of the DWT.
- The number of vanishing moments determines the response pattern of the signal in consideration. This is due to the sharp fall-off signal behavior in the transition frequency bands that make the nearby frequency bands get less energy.

One of the main demerit of using the wavelet transforms in signal analysis is that there is no internationally set regulations and standards for choosing the appropriate wavelet to use and the sub band to suit a given application. One has therefore to rely on the statistical measures in order to arrive at a given wavelet to put into use.

After the sampling and extraction of the signal by DWT, the signal was subjected to fuzzy logic to classify the scenario as islanded or not islanded. Mamdani fuzzification model was used in implementing the rules and centroid method was used in defuzzification the output. First, the algorithm was able to distinguish islanding condition from non-islanding condition as shown in figure 4.10.

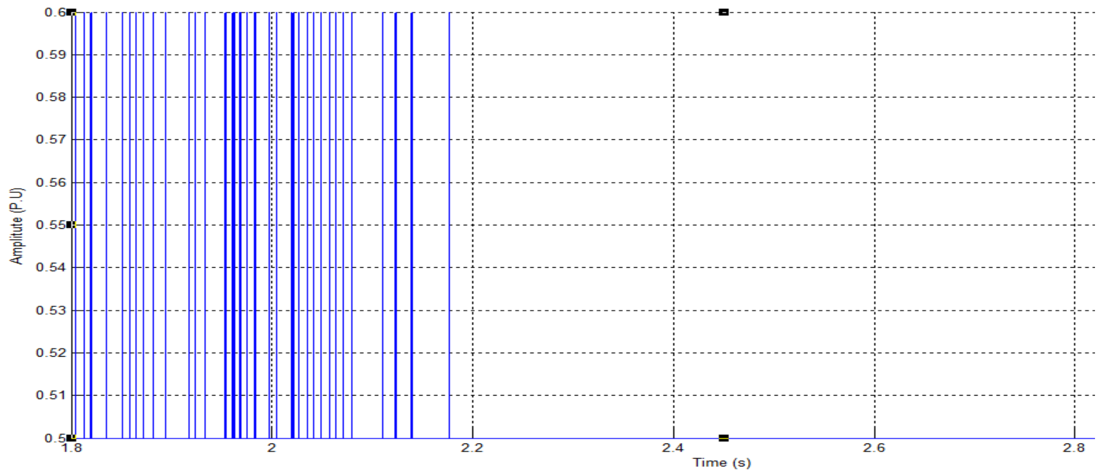

Figure 4.10: FLC output

Then the frequency measurement was done and the result is as shown in figure 4.11. As it can be seen, the frequency varies from the normal on the 2nd second as soon as the CB is opened. This is as a result of opening the CB after 2s to create an island for islanding detection analysis. Then after 0.4 seconds the system stabilizes and the frequency variation from the nominal value remains constant throughout the islanding time.

The system frequency varies from zero seconds as the system is switched on. This is the duration the system is initializing before stabilizes.

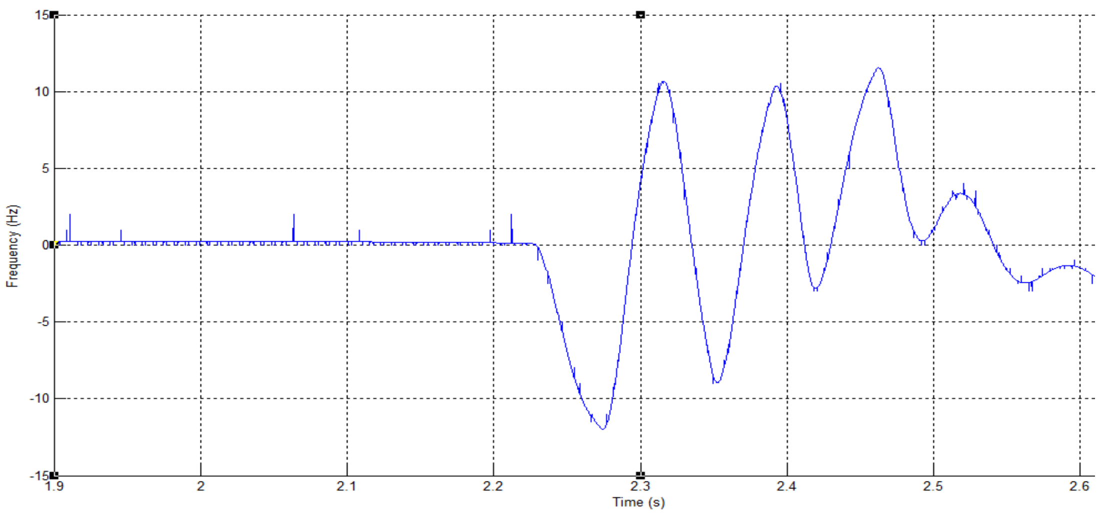

Figure 4.11: Frequency deviation measurement

The rate of change of power (ROCOP) was also measured and its result is as shown in figure 4.12. It is noted that there is a sharp change on the 2nd second when the circuit breaker opens to create an island. Later on, it returns to the normal position. This is due to the voltage regulator which restores the system back immediately. The rate of change of power is normally used to measure the impact the active power variations have on frequency and the voltage of the system. When the DG is operating with mains, the impact is usually small. However, this is not the case when the DG is operating in an island.

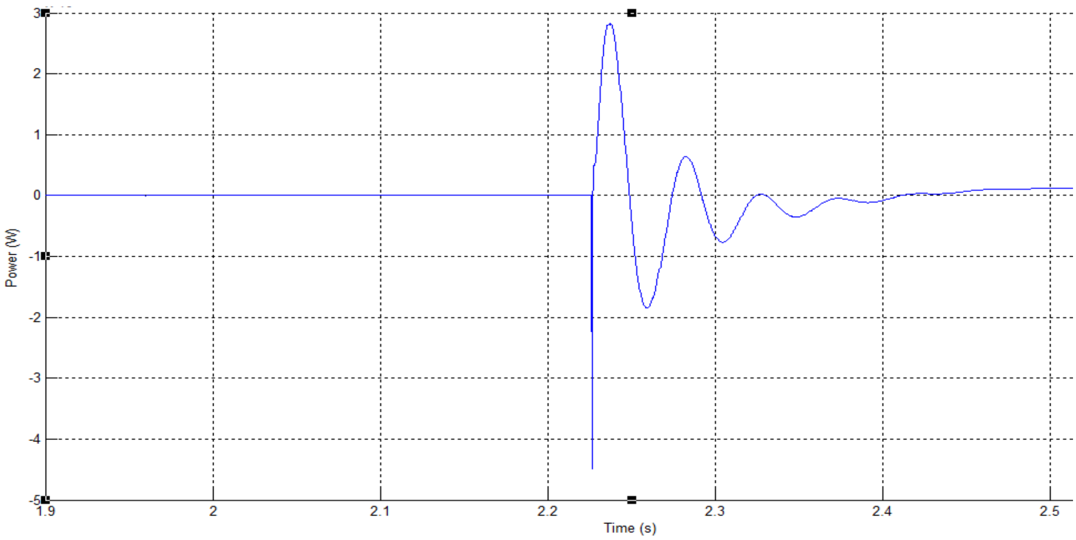

Figure 4.12: Rate of change of power

Lastly, the rate of change of frequency was measured and the result is as shown in figure 4.13. Unlike frequency deviation, there is no significant change when the CB is opened to create an island. It is after being combined with another system measurements like ROCOP and the system frequency deviation that the combined effect of determining whether an islanding condition has taken place or not can be determined. Otherwise nothing much can be interpreted from the observation of the rate of change of frequency alone.

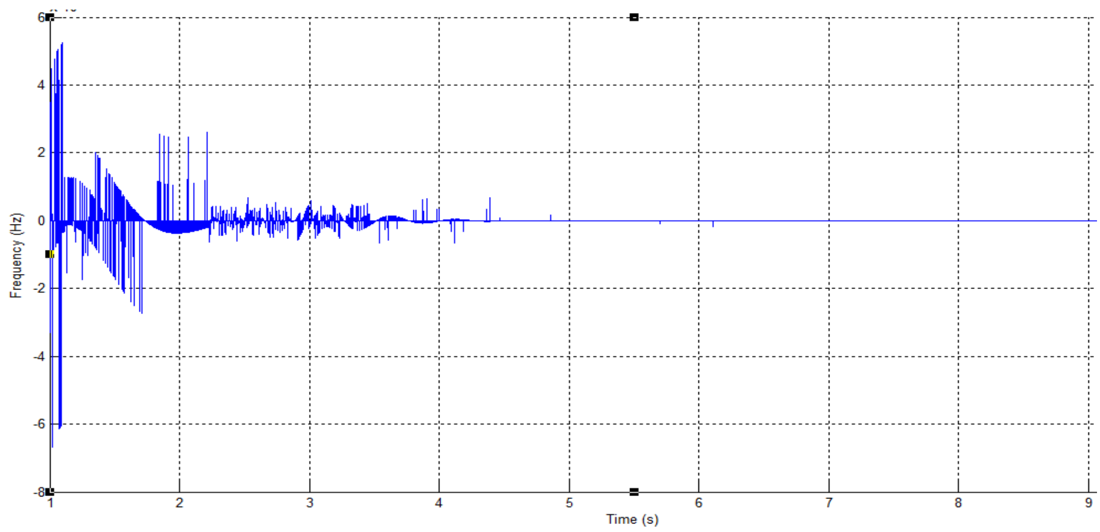

Figure 4.13: Rate of change of frequency

The generator field current and voltage was observed throughout this analysis and it characteristic is as shown in figures 4.14 and 4.15. From the principle of operation of SDGs, a direct current (DC) is normally applied to the windings of the rotor so as to produce the magnetic field at the rotor. Then by using some external means this generator rotor is turned in order to generate the rotating field, that generates by induction a three-phase voltage within the winding of the stator. The operation of synchronous machines is greatly influenced by the field currents. For instance, it determines the value of the of the power factor and the machine load angle especially when the SDG is operating as a standalone network. Therefore, proper control of this field currents can greatly improve the stability of the SDGs and also during transient states of these machines.

As it can be observed from figure 4.10, the islanding detection time is 0.2 seconds. By detecting the islanding in this very short time, the NDZ is greatly reduced. In ideal situation, the NDZ should be zero.

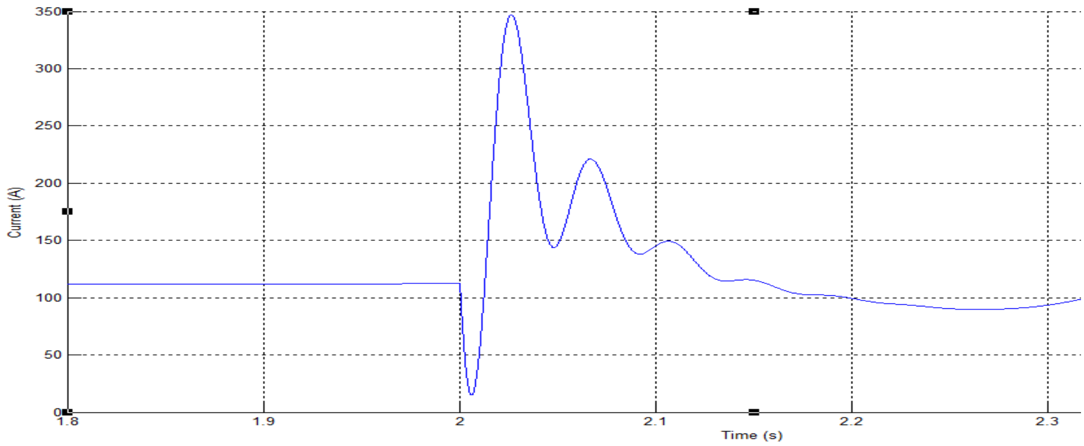

Figure 4.14: Generator field current

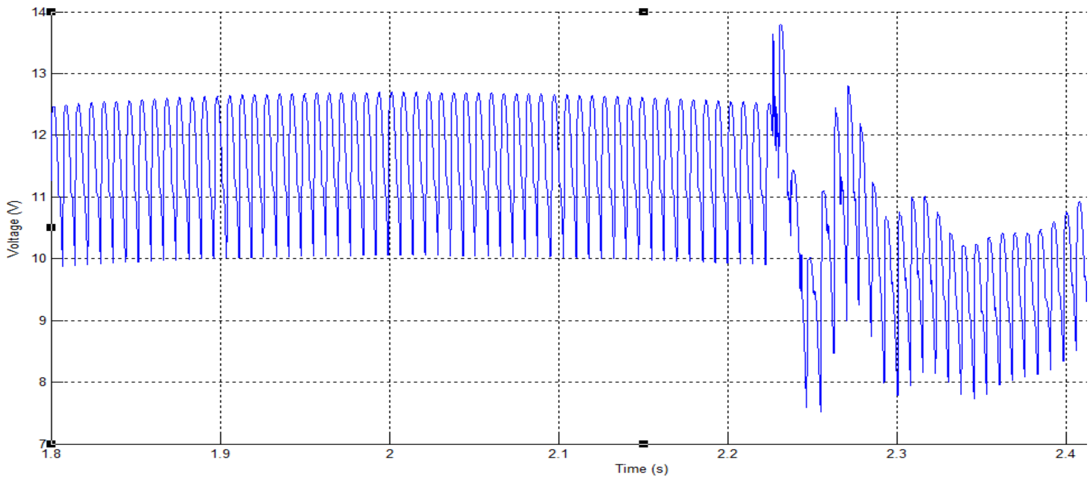

Figure 4.15: Generator field voltage

4.2 Power Prioritization using ABC Algorithm

On the part of power optimization and prioritization within the islanded region, the IEEE fourteen bus was used in the analysis but with little modification on the bus data and line data. The distributed generator of 320MW was connected at bus number two and a number of loads connected at different buses totaling to 362MW. Both the generator output and the connected load was varied from 270MW to 362.5MW at the intervals of 30MW and the signal variations observed.

Then using ABC algorithm and load flow, we were able to determine the power deficit and surplus in the island. In addition to this, the buses were given priorities and buses to be shed were picked based on the amount of deficit and the bus priority. Table 4.1 is a snapshot of the system results obtained when a total of 362.5MW load was connected to a 320MW generation. From the simulation, the line losses were 32.805MW and the total load to be shed should be 75.305MW including line losses.

Table 4.1: Prioritization results

Bus no.	**Injection**		**Generation**		**Load**
	MW	**MVAR**	**MW**	**MVAR**	**MW**
1	75.305	0.000	75.305	0.000	0.000
2	298.300	0.000	320.000	0.000	21.700
3	-94.200	0.000	0.000	0.000	94.200
4	-47.800	0.000	0.000	0.000	47.800
5	-7.600	0.000	0.000	0.000	7.600
6	-11.200	0.000	0.000	0.000	11.200
7	-0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000
9	-30.000	0.000	0.000	0.000	30.000
10	-30.000	0.000	0.000	0.000	30.000
11	-30.000	0.000	0.000	0.000	30.000
12	-30.000	0.000	0.000	0.000	30.000
13	-30.000	0.000	0.000	0.000	30.000
14	-30.000	0.000	0.000	0.000	30.000
Total	32.805	0.000	395.305	0.000	362.500

Power generated = 320.000 MW

Power demand = 362.500 MW

Losses = 32.805 MW

Load to shed = 75.305MW

Bus to shed = 14

4.2.1 Constant Demand and Constant Supply Characteristics

Then the connected load was kept constant and the generator output varied and observations made. This is shown in table 4.2 below.

Table 4.2: Constant demand with varying supply

Simulation	Power generated	Power demand	Losses	Load to shed	Shed bus
1	352.500	362.500	33.817	-	-
2	330.000	362.500	32.983	65.483	14
3	300.000	362.500	32.563	95.063	14 & 13
4	270.000	362.500	32.486	124.986	14, 13 & 12

On the other hand, the generator output was kept constant and the connected load varied and observations made. This is illustrated in table 4.3 below.

Table 4.3: Constant supply with varying demand characteristics

Simulation	Power generated	Power demand	Losses	Excess generation
1	362.500	362.500	33.817	33.817
2	362.500	352.500	28.568	18.568
3	362.500	342.500	27.281	7.281
4	362.500	335.500	26.259	-3.741

This excess generation is the one to be connected to the dummy loads since the system is already operating as an island. The negative figure in excess generation is actually a deficit and not excess generation.

4.2.2 IEEE 14-Bus Test System

The occurrence of the islanding condition was successfully identified using DWT and FL as has been illustrated above, the load shedding of various buses was tested using an IEEE 14-bus test system. This system consists of five synchronous machines, including one synchronous compensator used only for reactive power support and four generators located at buses 1, 2, 6, and 8. In the system, there are twenty branches, fourteen buses and with 11 loads connected. The complete data of this test system is taken from 'Power system test case archive, University of Washington, Department of Electrical Engineering, from http://www.ee.washington.edu/research/pstca/index.html). The 14-bus data, line data and the bus connections are shown in appendix A, B and C respectively.

The priorities for load shedding was arbitrarily set in the following decreasing order for Load buses 1-14. Out of these selected buses bus 14 is the one having least priority followed by 13 and so on. Therefore, in case the supply is less than the connected loads, bus number 14 will be the first one to be shed followed by 13 in that order until supply and load demand balances.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

When compared with the inverter based DGs, the rotating machine based DGs with fast response governors and AVRs are highly capable of sustaining an island the moment it occurs. Therefore, islanding detection and protection for this kind of generators becomes a more challenging problem in comparison with the inverter based generators.

Hence, in light of this challenge, this research work looked in depth the various methods currently used in the islanding detection especially for rotating machine based DGs and analyzed them in detail by use of the DWT and FL control methods.

From this analysis, it was observed that there was a quick response to islanding detection due to the changing of the point of measuring of the current signals from the usual PCC to just after the utility circuit breaker. It took 0.2 seconds for this algorithm to detect the occurrence of the island. This is because the islanding detection time is not affected here by the network circuit breaker operation time. Thus, making the detection process faster thus reduction in NDZs in this system.

In most cases, the currently utilized islanding detection methods detect occurrence of an island much after an island has already been created. This is due to the monitoring of the fluctuations of the voltage, current or frequency at the PCC as a result of the grid disconnection or circuit breaker opening due to fault. In this method, islanding condition is detected before an island is created or before the circuit breaker trips. By merely changing the measurement point from the PCC this method overcomes the drawbacks associated with the local methods.

Generally, the results obtained show that this islanding detection method is able to detect islanding operation quickly and in an efficient way when put in use. As it is mentioned, for detecting the islanding condition, this study presented an online measurement method based on wavelet transform combined with fuzzy logic for current and voltage analysis. The positive results obtained here could be described in briefly by the following two points:

- By simply extracting the signals before the main circuit breaker, the islanding detection time decreases tremendously as required by the IEEE 1547-2003 standard.
- There is improved reliability of the system as a result of using the transient signals sent from network with minimum noise effects.

This method of detecting the presence of islands for rotating machine based generators in the network is more accurate, robust and gives more reliable results when it is implemented in the distribution network. This is because of the fuzzy logic control's ability to improve the interpretability of signals through its semantics that provide insight in the classification structure and the process of making decision as unlike the crisp classifiers.

Another merit of FL in this application is its ability to tolerate more noise falling along its trapezoidal membership functions. In addition to this, it has smooth boundaries unlike the other crisp classifiers such as decision tree. This method is therefore more appropriate to be used in online islanding and non-islanding detection in a large power grids.

Now that intentional islanding of sections of the grid is the future of the smart grid, this method is more suitable to be applied in the intentional islanding to enhance the reliability of the power system. Also, the simulation results provided in this study have

successfully proven that this method provides better islanding detection time and performance in comparison with the existing detection methods. This method of islanding detection has a number of advantages that includes, these include;

- The non-detection zones, NDZs, that happen to be a major drawback of most of the passive methods of islanding detection are highly mitigated.

- This method of islanding detection is more cost effective when compared with the remote methods that use power lines for communications.
- This method can be used to mitigate if not to eliminate power blackouts in the distribution systems.
- Unlike the active and the hybrid islanding detection methods, this proposed method of islanding detection doesn't introduce any perturbation into the power systems hence improving the stability and the quality of power supplied to consumers from the system.

The last part of this study involved finding the optimal load to be shed and the selection of the buses to be shed using the ABC algorithm. The main objective of shedding some loads is to provide smooth and gradual load relief, in situations where the power system would become uncontrollable and go unstable. The buses for load shedding are selected based on the priority attached to those buses and the required amount of load to be shed.

In this study, the ABC algorithm was successfully applied for solving the optimization and prioritization problems in the island being supplied by the DG. The ABC algorithm is based on the foraging behavior of honey bees for finding global and local solution for optimization problems. The advantages of using this algorithm are its robustness, fast calculation of the error, flexibility, and few parameters to be set. However, the ABC algorithm suffers a drawback of the search space limited by initial solution. In fact, this drawback can be overcome using normal distribution sample in the initial step.

This proposed algorithm has been tested on a fourteen-bus system and the obtained result for this system was analyzed and it was satisfactory to draw concrete conclusions. In comparison with other methods of optimization, the proposed algorithm can obtain better optimal solution than many other methods with a fast-computational manner, especially for large-scale systems. Therefore, the ABC algorithm can be a favorable method for solving optimization and prioritization problems in power systems.

5.2 Recommendations

Due to the continued use of the DGs in the distribution system of the electric power grids, more research needs to be done on this area in addition to the already carried out researches. The following are some of the recommendations:

- Several issues remain un clear and should be considered for the future works within distribution networks such as using other classification methods and also using other sample signals like frequency deviation, and using other time frequency analysis methods such as S-transform in place of the wavelet transform.
- This analysis has been carried out on IEEE 14 bus system whereby only one DG was put into consideration. To broaden this concept, the performance of these algorithms should be studied on other IEEE bus systems and power distribution networks with multiple DG interface.

5.3 Journal Publications and Conference Proceedings from this Study

1. L. Mogaka, D. K. Murage, M. J. Saulo. "Power Optimization and Prioritization in an Island Supplied by a Rotating Machine Based Distributed Generator Using Artificial Bee Colony Algorithm". International Journal of Energy and Power Engineering. Vol. 5, No. 1, 2016, pp. 15-21. doi: 10.11648/j.ijepe.20160501.13.
2. Lucas Ongondo Mogaka, D. K. Murage, Michael Juma Saulo. "Rotating Machines Based Islanding Detection Using Fuzzy Logic Method Analysis". International Journal of Energy and Power Engineering. Vol. 4, No. 5, 2015, pp. 311-316. doi: 10.11648/j.ijepe.20150405.21.
3. Lucas Ongondo Mogaka, D. K. Murage, Michael Juma Saulo. "Rotating Machine Based DG Islanding Detection Analysis Using Wavelet Transform".

International Journal of Energy and Power Engineering. Vol. 4, No. 5, 2015, pp. 257-267. doi: 10.11648/j.ijepe.20150405.14

4. L. Mogaka, D. Murage, M. J. Saulo. "Synchronous and induction machine based distributed generation islanding detection: an overview". Proceedings of the sustainable research and innovation (SRI) conference, 6-8 may, 2015, pp. 158-162, ISSN: 2079-6226
5. L. O. Mogaka, M.J Saulo, D. K. Murage "Rotating Machine Based DG Islanding Detection Analysis Using Wavelet Transform". The 10th JKUAT Scientific, Technological and Industrialization Conference and Exhibitions. 12th - 13th November 2015
6. L. Mogaka, D.K. Murage, M.J. Saulo. "Rotating Machine Based Power Optimization and Prioritization Using the Artificial Bee Colony Algorithm". Proceedings of the sustainable research and innovation (SRI) conference, 4-6 may, 2016, pp. 87-93, ISSN: 2079-6226

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APPENDICIES

Appendix A: Fourteen Bus Data

Bus No	Bus Code	Voltage Magnitude	Angle Degrees	Load		Generator				Injected MVAR
				MW	MVAR	MW	MVAR	Qmin	Qmax	
1	1	1.06	0	30.38	17.78	40	-40	0	0	0
2	2	1.045	0	0	0	232	0	-40	50	0
3	2	1.01	0	131.88	26.6	0	0	0	40	0
4	0	1	0	66.92	10	0	0	0	0	0
5	0	1	0	10.64	2.24	0	0	0	0	0
6	2	1.07	0	15.68	10.5	0	0	-6	24	0
7	0	1	0	0	0	0	0	0	0	0
8	2	1.09	0	0	0	0	0	-6	24	0
9	0	1	0	41.3	23.24	0	0	0	0	0
10	0	1	0	12.6	8.12	0	0	0	0	0
11	0	1	0	4.9	2.52	0	0	0	0	0
12	0	1	0	8.54	2.24	0	0	0	0	0
13	0	1	0	18.9	8.12	0	0	0	0	0
14	0	1	0	20.86	7	0	0	0	0	0

Bus codes

0 = Slack bus

1 = PQ bus

2 = PV bus

Appendix B: Fourteen Bus Line Data

Sendind end Bus	Receiving end Bus	Resistance p.u.	Reactance p.u.	Half Susceptance p.u.	Tranformer tap
1	2	0.01938	0.05917	0.0264	1
2	3	0.04699	0.19797	0.0219	1
2	4	0.05811	0.17632	0.0187	1
1	5	0.05403	0.22304	0.0246	1
2	5	0.05695	0.17388	0.017	1
3	4	0.06701	0.17103	0.0173	1
4	5	0.01335	0.04211	0.0064	1
5	6	0	0.25202	0	0.932
4	7	0	0.20912	0	0.978
7	8	0	0.17615	0	1
4	9	0	0.55618	0	0.969
7	9	0	0.11001	0	1
9	10	0.03181	0.0845	0	1
6	11	0.09498	0.1989	0	1
6	12	0.12291	0.25581	0	1
6	13	0.06615	0.13027	0	1
9	14	0.12711	0.27038	0	1
10	11	0.08205	0.19207	0	1
12	13	0.22092	0.19988	0	1
13	14	0.17093	0.34802	0	1

Appendix C: IEEE 14 bus