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An Islanding Detection Method for Micro-Grids With Grid-Connected and Islanded Capability

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AN ISLANDING DETECTION METHOD FOR MICRO-GRIDS WITH GRID-CONNECTED AND ISLANDED CAPABILITY

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Under the Supervision of Dr. Ala Hussein

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Declaration of Original Work

I, Hasna Mubarak Saleh Al Seiari, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*An Islanding Detection Method for Micro-grids with Grid-connected and Islanded Capability*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Ala A. Hussein, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Copy 11 of 12

Abstract

With the increasing prevalence of renewable energy and distributed generation (DG) in distribution systems, micro-grids are becoming more popular and an attractive option for enhancing system operation and reliability. This can be attributed to the micro-grid's ability to operate in both connected and disconnected modes. Equally important, micro-grids are the best solution to meet the increasing demand of electric power in a cost effective manner due to the close proximity to the load demand and thus minimizing system losses. Islanding detection methods have been proposed for inverter based distributed generation with only grid-connected capability. Micro-grids are composed of DGs that are capable of operating in two modes: grid connected and islanded. This thesis introduces and proposes the concept of micro-grid transition detection where the status of the micro-grid is detected based on adaptively modifying the droop slope. The droop coefficient is chosen such that the micro-grid is stable while grid connected and in the contrary unstable once an islanded micro-grid operation is initiated. The droop coefficient is adaptively modified, once the micro-grid transitions from grid-connected to islanded operation, to stabilize the micro-grid for the islanded mode of operation. The proposed method is capable of detecting micro-grid transition in less than 600 ms under various active and reactive power mismatches. The proposed micro-grid transition detection method is tested on a micro-grid equipped with inverter based DGs controlled using the droop approach. The main objective of this thesis is to develop a novel islanding detection method for micro-grids with grid connected and islanded capability. A micro-grid model was developed using power system computer aided design/ electromagnetic transient and DC (PSCAD/EMTDC) as a platform for testing the proposed method. Simulation results were conducted considering the Institute of Electrical and Electronics Engineers Standard 1547(IEEE Std. 1547) standard islanding detection testing procedure.

Keywords: Distributed Generators, Inverters, Micro-grids, Islanding Detection, Droop Control.

Title and Abstract (in Arabic)

طريقة الكشف عن ظاهرة التجزر في الشبكات الكهربائية الدقيقة سواءً كانت متصلة أو منفصلة

الملخص

مع تزايد الطلب على الطاقة المتجددة وموزعات الطاقة في نظام التوزيع الكهربائي ، أضحى استخدام الشبكة الكهربائية الدقيقة منتشرًا و يحضى باهتمام شديد لا سيما و أنه يعتبر خيارًا جذابًا نظرًا لقدرة الشبكة الكهربائية الدقيقة على تحسين و تعزيز عمل و كفاءة النظام . و لعل هذا يرجع إلى قدرة الشبكة الكهربائية الدقيقة على العمل في كلتا النمطين المنفصل و المتصل .إضافة إلى ذلك ، تعتبر الشبكة الكهربائية الدقيقة الحل الأمثل لتلبية الاحتياج المتزايد للطاقة الكهربائية من ناحية الكلفة و الكفاءة و بالتالي تقليل خسارة النظام. تم طرح و اقتراح طرق الكشف عن احتمالية وجود تجزر بالنظام الكهربائي مثل قطع الكهرباء لموزع الطاقة المرتكز على المحول في حالة كانت الشبكة متصلة فقط . الشبكة الكهربائية الدقيقة من موزعات الطاقة القادرة على العمل في النمطين سواء المتصل أو المنفصل . تهدف الأطروحة لتقديم و اقتراح مفهوم الشبكة الكهربائية الدقيقة القادرة على كشف التجزر في النظام الكهربائي في حالة كانت الشبكة الكهربائية الدقيقة تعتمد على تعديل الميل. يتم اختيار معامل الميل حيث أن الشبكة الدقيقة تكون مستقرة في حالة اتصالها مع الشبكة و على العكس تكون غير مستقرة في حالة التجزر.يتم تعديل معدل الميل حيث أن تحول الشبكة الكهربائية الدقيقة من شبكة منفصلة إلى أخرى في حالة كشف التجزر و ذلك لتعديل حالة الشبكة. بالتالي يكون الهدف الرئيسي وراء هذه الأطروحة هو استحداث طرح جديد لطرق كشف التجزر في النظام الكهربائي ، مثل انقطاع التيار، باستخدام الشبكة الكهربائية الدقيقة سواء كانت الشبكة منفصلة أم لا و سيكون (PSCAD/EMTDC) مثل قاعدة انطلاق لتطبيق الطريقة المبتكرة المقترحة. سيكون عرض النتائج و مقارنتها باستخدام معيار (IEEE Std. 1547).

مفاهيم البحث الرئيسية: موزعات الطاقة ، المحول ، الشبكات الكهربائية الدقيقة ، كشف التجزر ، متحكم الميل.

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Dedication

To my beloved Mom and family

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AFDPF	Active Frequency Drift with Positive Feedback
AFD	Active Frequency Drift
Cf	Chopping Fraction
CSI	Current Source Inverter
d-axis	Direct Axis
DG	Distributed Generation
DNO	Distribution Network Operator
DR	Distributed Resource
HATS	Hybrid Automated Transfer Switch
IDMs	Islanding Detection Methods
IEEE Std.1547	Institute of Electrical and Electronics Engineers Standard 1547
m	Modulation Index
mp1	Stable Droop Gain Value
mp2	Unstable Droop Gain Value
NDZ	Non-Detection Zone
PCC	Point of Common Coupling
PF	Positive Feedback
PI Controller	Proportional, Integral Controller
PJD	Phase-Jump Detection
PLCC	Power Line Carrier Communication
PLL	Phase Locked Loop
PSCAD/EMTDC	Power System Computer Aided Design/ Electromagnetic Transient and DC

PV	Photovoltaic
q-axis	Quadrature Axis
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SFS	Sandia Frequency Shift
SMS	Slip Mode Frequency Shift
SVS	Sandia Voltage Shift
theta	Modulation Signal Angle
T_{Vutil}	Period of utility voltage
T_Z	Dead Time
UFP/OFP	Under/Over Frequency Protection
UTSP	Unified Three Phase Signal Processor
UVP/OVP	Under/Over Voltage Protection
VSC	Voltage –Sourced Converter
VSI	Voltage Source Inverter
VU	Voltage Imbalance

Chapter 1: Introduction

1.1 Overview

With the increased interest in DG and renewable energy, micro-grids have gained growing attention in recent years. There are various challenges associated with the operation of micro-grids such as include control, protection, planning. One important key aspect, is the detection of the transition of the micro-grid from grid connected to islanded mode. This thesis will address this issue by proposing a novel approach for detecting the islanded condition of a micro-grid equipped with droop control, which is one of the most commonly applied methods for controlling micro-grids. The proposed detection method relies on adaptively modifying the droop slope, such as the droop gain value prior to islanding, creating instability, and allowing islanding detection. Once islanding is detected, the droop gain adaptively changes to stabilize the voltage and frequency of the micro-grid within the IEEE Standard threshold values.

1.1.1 Micro-Grids

With the increased prevalence of conventional and renewable resources in the power system, it was necessary to cope with these changes in order to operate in an efficient and intelligent way. In other words, it is important to design new approaches that would allow the supply of excessive future electricity demand with less cost expenditure. A new concept that has emerged recently, which is the micro-grid approach, that focuses on creating a design and plan for local energy delivery meeting the exact needs of the community constituents being served such cities, hospitals, universities. Micro-grids are composed of a group of DGs connected to the distribution system with both grid connected and islanded capability [1]. This definition establishes four core functions of a micro-grid [2]:

1- To regulate the voltage amplitude and frequency in a micro-grid within a normal rate when functioning in the islanded mode.
2- To allocate each power from an energy resource, whether active or reactive power, to load when operating in the islanded mode.
3- To enable power exchange between a micro-grid and the utility in the grid-connected mode.
4- To ensure easy transfer between the islanded mode and the grid-connected mode.

Traditional centralized generating systems can sometimes be unable to meet the potential growth of future electricity demand at acceptable cost. Thus, micro-grids are expected to cope with these changes positively on a technical, economic and environmental level. Technically speaking, micro-grids establish a reliable plan that integrates redundant distribution, smart switches, automation, and independent power generation and storage in order to solve emerging issues and eliminate black-outs. Smart switches and sensors fix and anticipate power disturbances unlike traditional ones. Equally important, micro-grids can provide voltage support, improve power quality as well as increase system reliability by supplying power during utility outages [3].From the economic perspective, DGs can supply the customers by constructing new distribution lines that can meet their needs especially for remote places that cannot easily be supplied by the utility. Three main stakeholders; the DG owner, distribution network operator (DNO), and the customer can benefit economically from installing DGs. The DG owner can get additional revenue and reduce expenditure by selling excess power during utility outages. However, the

DNO would gain better security over the entire network as the DG's main task is to maintain safety. In fact, the main stakeholder, who is the customer, would certainly gain since the DG will reduce the cost as long as it reduces frequency and duration of power interruption [4]. Overall, the DG helps gain important amounts yearly due to transmission congestion that mainly occurs when insufficient energy is available to meet the demands of all customers, thereby affecting general electricity market prices [5]. From a futuristic point-of- view, this technology is strongly needed to be a part of today's vision by finding eco-friendly solutions with the use of micro-grids. It is a proven method for the future as it can meet known and unknown future needs by allowing communities to increase overall electricity supply quickly and efficiently through renewable energies such as small local generators, solar cells, and wind turbines. In addition, smart grids enable plug-in-electric vehicles. The ability to use local renewable or natural gas energy generation will make this a more versatile system. Smart grids can reuse the energy produced during electricity generation for heating building, hot water, and sterilization [6]. In the literature, various protection as well as control techniques have been proposed for micro-grids in recent years.

One major challenge is that micro-grids can be designed to operate in two modes, namely, the grid-connected mode and the islanded mode. This requires several key aspects that include control, synchronization, and islanding detection, as shown in Figure 1 [7].

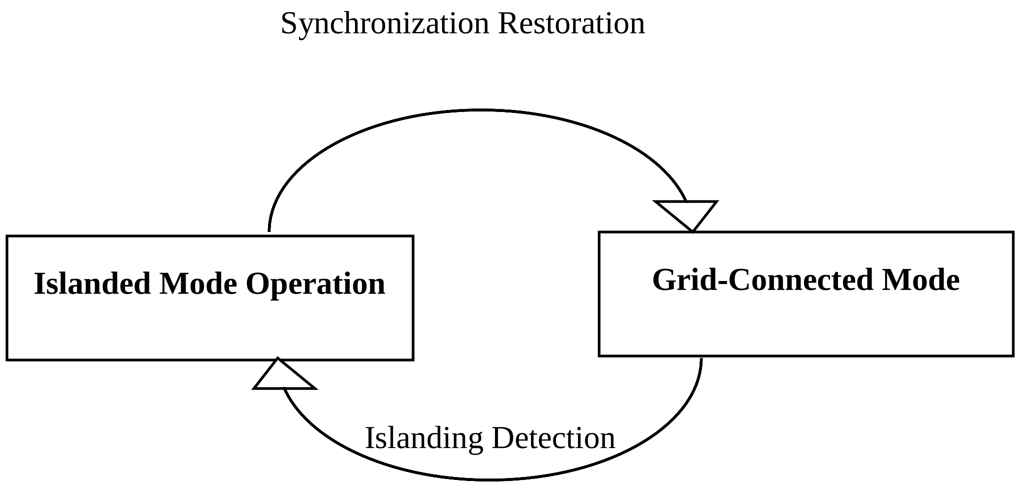

Figure 1: The modes of the micro-grids operation

1.1.2 Islanding Detection

Since islanding occurs when the whole electricity distribution system becomes isolated or disconnected from the rest of the electrical power system but remains energized by a distributed resource (DR) [8] , it was essential to understand how the islanding phenomena takes action to avoid islanding problems . Islanding can have negative impacts on system operation as well as safety issues if not detected and configured on time. For instance, some of the islanding key issues are mainly related to power quality, safety, and operation. Technically speaking, power quality can be threatened when islanding occurs and can cause damage to voltage and frequency, which cannot be maintained within a standard permissible level. Moreover, the islanded system may be inadequately grounded by the DG interconnection. In addition, islanding can have serious health and safety issues especially for the line worker. Operationally speaking, instantaneous reclosing could result in out-of-phase reclosing of the DG causing damage to the utilities' and customer's equipment [9]. There are various islanding risks, and they are serious since it also includes degradation of electric components resulting unstable voltage and frequency.

In fact, detecting an islanded condition is separated into two main methods; remote and local .For instance, the remote method focuses mainly on creating a communication interface between utilities and DGs. However, the local method is based on measuring certain system parameters at the DG site. The local method detects islanding through three main techniques, which are passive, active, and hybrid. Passive techniques are based on monitoring some parameters and comparing them with the threshold value to detect the islanding. A positive point of this technique is that its implementation does not have an impact on the normal operation of the DG system. Active techniques work by introducing a small perturbation in the power system and monitoring the change in system parameters, when the DG is islanded. The active technique's main positive feature is the high islanding detection response that can cover most of the area, and this is described as small a non-detection zone unlike in the passive technique. The hybrid technique employs both active and passive detection characteristics to detect the islanded condition.

Various islanding detection methods will be highlighted in the following chapters.

1.2 Objectives

The purpose of this research is to introduce and propose an innovative micro-grid islanding detection method that works in both connected and islanded capability unlike the previous method that works only when the grid is connected. The detailed objectives of this work are as follows:

- Develop a micro-grid model with multiple inverter based DGs equipped with droop using PSCAD as a platform for testing the proposed method.
- Determine the best utilized droop gain using transient models during grid-connected and islanded operation, while maintaining the stability of the system.
- Develop a novel islanding detection method with particular focus on micro-grids.

1.3 Outline of the Thesis

This thesis is outlined in five chapters. Chapter One offers a general overview of both, the studied and proposed work while touching on the possible future research contribution.

Chapter Two includes a literature review and compares numerous detection techniques and islanding detection for micro-grids and then highlights their advantages and disadvantages.

Chapter Three provides a detailed description of the proposed method and determines its operations in single and multiple DGs.

Simulation results are available in Chapter Four, where a general yet in-depth discussion of the proposed method results is outlined.

Finally, Chapter Five states the research's general conclusion with the scope of a futuristic work.

Chapter 2: Literature Review

2.1 Islanding Detection Techniques

Islanding detection of distributed generations is a vital feature that enables all DGs to be connected to the distribution system. An overview of power system islanding methods is highlighted in this chapter. The methods are broadly divided into two main types: remote and local as shown in Figure 2 [10]. The remote islanding detection method concerns the utility side, whereas, the local method is related to the DG side. The local method can be classified into three main techniques; passive, active, and hybrid.

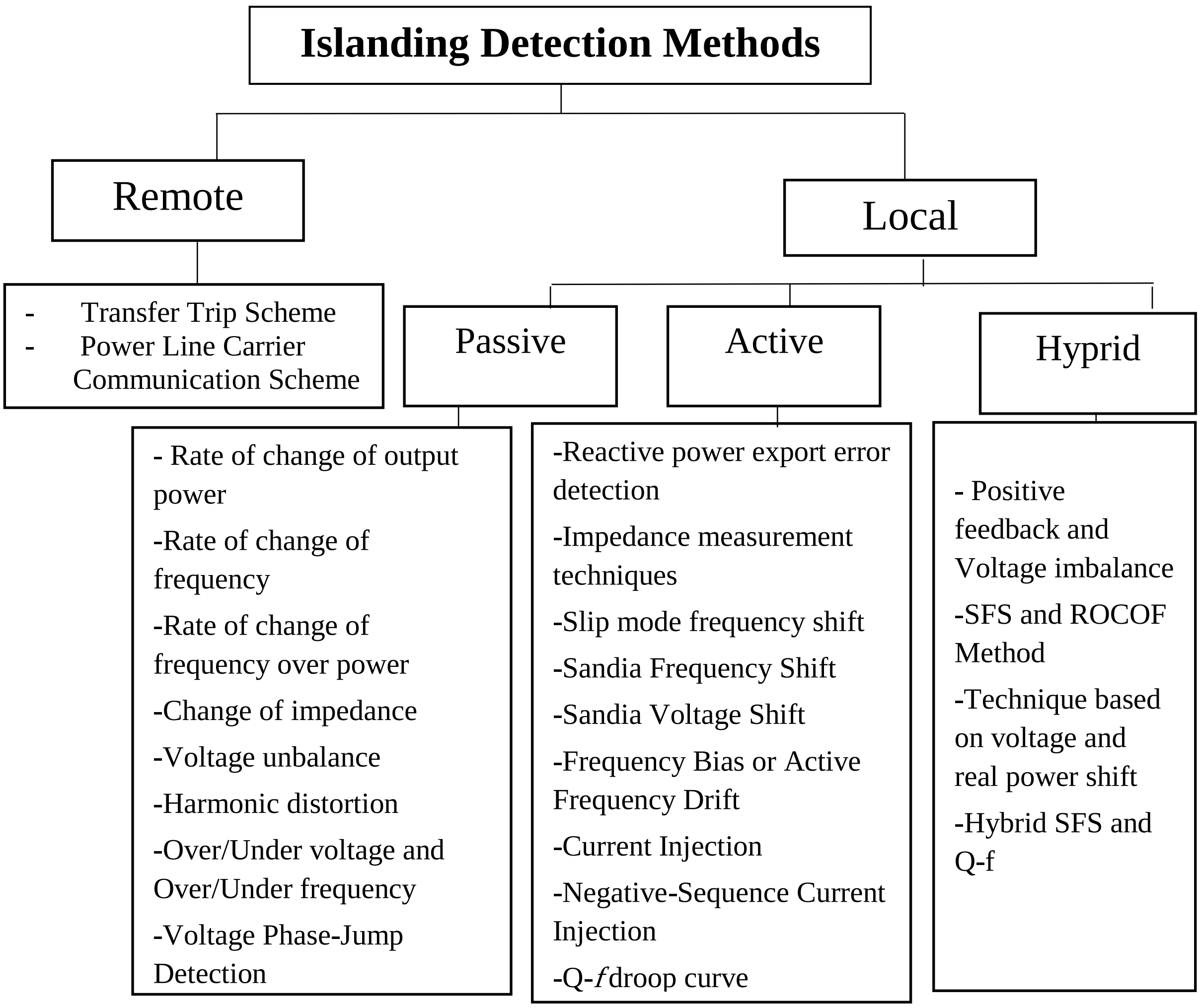

Figure 2: Islanding detection techniques

2.2 Remote Islanding Detection Techniques

The detection of the islanded condition problem can be done through the remote method that is mainly the transfer trip scheme and the power line communication scheme. They are based on the communication between utilities and the DG. These variations of the remote method have been considered more reliable than local ones in different, although they have been regarded as very expensive and hence uneconomical [10].

2.2.1 Transfer Trip Scheme

A transfer trip scheme can be defined as the way of monitoring specific circuit breakers and re-closers in a distribution system for the purpose of island detection [11].To monitor this, the transfer trip scheme collaborates with supervisory control and data acquisition (SCADA). This method needs a good and strong communication between the utility and the DGs.

2.2.2 Power Line Carrier Communication Scheme (PLCC)

PLCC is responsible of broadcasting a signal in the transmission system to the distribution feeders using the power line as signal carrier. In each DG, there is a receiver that receives signals. Once it does not detect a signal, the switch from grid-connected to islanded mode occurs [12].The power line scheme is viewed as an effective detection method in the case of multiple DGs.

2.3 Local Islanding Detection Techniques

Other alternatives to monitor island problems are the local detection techniques that are basically based on the measurement of the system parameters on the DG side like voltage, frequency, etc. These techniques vary between passive, active, and hybrid.

2.3.1 Passive Detection Techniques

The passive methods are used when there is a large mismatch in generation and demand in the islanded system. These techniques are based on monitoring some parameters like voltage, frequency, harmonic distortion, etc. and comparing it with the threshold value to detect the islanding [13]. These techniques are fast and do not cause system disturbance, but have a large non-detectable zone (NDZ) .Figure 3, illustrates the flow chart of the passive detection technique's process. Several passive islanding detection techniques are introduced and some of them are as follows:

2.3.1.1 Rate of Change of Output Power

In case of islanding, the rate of change of output power after the islanded condition is greater than the rate of change of output power before the islanded condition [11].This method is effective when an unbalanced load occurs in the distribution system.

2.3.1.2 Rate of Change of Frequency

The rate of change of the frequency in islanding is greater than the rate of change of the frequency when connected to the grid [14]. This method is reliable when there is a large mismatch in power.

2.3.1.3 Rate of Change of Frequency Over Power

This method detects the island by using the rate of change of the frequency over power. In general, the rate of change of the frequency over power in a small generation system is larger than that of the large generation system. When islanding occurs, the rate of change of the frequency over power changes [15].Furthermore, it has been found that rate of change of the frequency over power is more sensitive than the rate of change of the frequency over time in the case of a small power mismatch between the DG and the local load.

2.3.1.4 Change of Impedance

In general, the impedance of the utility is smaller than the impedance of an island. In the case of islanding detection, the island impedance will increase [16]. Impedance has to be monitored continuously to track any islanding.

2.3.1.5 Voltage Unbalance

Whenever, the percentage of the unbalance voltage in the system changes drastically, islanding detection becomes easy by monitoring various parameters such as voltage magnitude, phase displacement, and frequency change [17].

2.3.1.6 Harmonic Distortion

Islanding detection in this scheme occurs by monitoring the change of total harmonic distortion (THD) in the system during islanding formation [17].

2.3.1.7 Over/Under Voltage and Over/Under Frequency

This technique simply works by measuring the voltage and/or frequency at the point of common coupling (PCC). If the measured values are greater than or less than the threshold values, this indicates the island is present [18].To detect abnormal conditions, protective relays such as under/over voltage (UVP/OVP) and under/over frequency (UFP/OFP), are placed on the distribution feeders.

2.3.1.8 Voltage Phase-Jump Detection

Generally, loads do not accept the voltage from the grid perfectly, which implies that the load's power factor is not perfect. However, grid-tie inverters have a power factor of 1, which can lead to changes in phase when the grid fails inducing island detection [19].

Henceforth, the phase-jump detection (PJD) is perfectly applied for current source inverters (CSI) which involves monitoring of phase difference between inverter terminal voltage (V_{PCC}) at the PCC and inverter output current ($I_{PV\text{-}inv}$) observed for sudden changes or jumps [20]. When islanding occurs, during the transition from normal operation to islanding mode, the phase angle of V_{PCC} will shift to match the phase angle of local load. This leads to a sudden phase change to the PCC. At this stage, the PJD method will locate this sudden phase angle change in order to detect islanding. The phase locked loop (PLL) is utilized to synchronize and track the phase of the grid signal through the inverter output and grid voltage during normal operation. The PLL stays in sync with the grid signal by tracking when the signal crosses zero volts. When the phase errors exceed a present value, the inverter is ceased operation. As seen previously, this method is not that perfect as it lacks accuracy and fails in detecting islands forming a large NDZ. The PJD has smaller NDZ compared to the classical standard relay circuit methods [21].

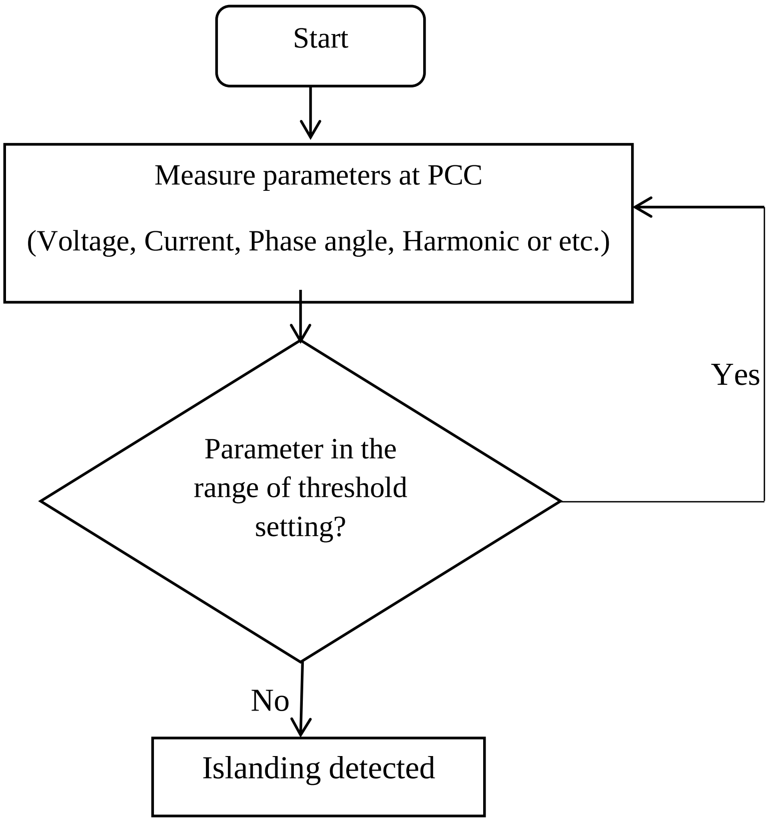

Figure 3: Flow chart of the passive islanding detection technique

2.3.2 Active Detection Techniques

The active islanding detection method is based on the injection of a small disturbance signal to certain parameters at the PCC [22].Unlike passive detection schemes, the active method has the ability to be detected under the perfect match of generation and load. That is to say, with this method even a small disturbance signal will become clear and noticeable when inferring the islanding mode of operation, so that the inverter will deal with the power change [23]. Figure 4, shows the flow chart of the active detection technique's process. A list of some of the active detection techniques is given below:

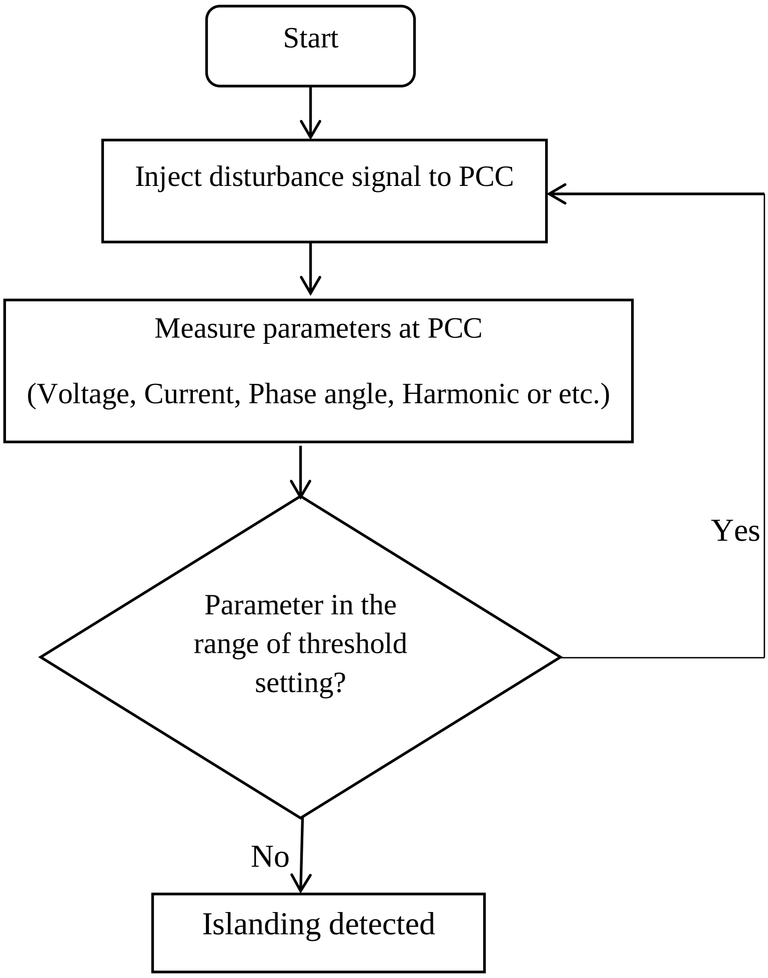

Figure 4: Flow chart of the active islanding detection technique

2.3.2.1 Reactive Power Export Error Detection

In this method, a level of reactive power flow is produced at the PCC between the DG side and the grid. It is important to note that the power flow can only be upheld when the grid is connected. The perturbation on the system happens by increasing the internal induced voltage from time to time and monitoring the change of the voltage and frequency. When a large change in voltage occurs with unchanged reactive power, this indicates an island [24].The main disadvantage of this method is that it is slow and cannot function in the system knowing that a DG has to generate power at unity power factor.

2.3.2.2 Impedance Measurement Techniques

Impedance measurement technique is used to address the islanding problem. It is simply injecting a high frequency signal on the DG terminal and monitoring the change of the high frequency [16].Once the frequency signal becomes significant, the grid gets disconnected. This method works by imposing a disturbance in one of the inverter parameters so that any perturbation in frequency, for example, will result in a perturbation of power.

2.3.2.3 Slip Mode Frequency Shift

Slip mode frequency shift (SMS) uses positive feedback to detect the islanded condition. SMS uses positive feedback to phase the voltage of the PCC [25]. When applying this method, the frequency will not be affected. In normal conditions, PV inverters function at unity power factor so that the phase angle is zero or close to zero. However, in the SMS method, this angle will operate to be a function of the frequency of the PCC voltage. An advantage of this method is that it can be easy to implement and operate [26]. Besides, this method has a small NDZ compared with other active methods.

2.3.2.4 Sandia Frequency Shift

The sandia frequency shift (SFS) method is a new method inspired from active frequency drift and is commonly known as active frequency drift with positive feedback (AFDPF), since it uses positive feedback to detect islanding [27]. In fact, the result of including positive feedback in this method can be shown in the following equation (1) [28]:

$$cf = cf_0 + K(f_{PCC} - f_{line}) \quad (1)$$

cf_0 is the chopping frequency with no frequency error, K is the gain of the controller, f_{PCC} is the frequency at the PCC, and f_{line} is the line frequency.

It is only when the utility is disconnected, that the frequency at the PCC increases the frequency error, which consequently results in the change in the frequency of the inverter, until reaching the threshold set for OFP, so that islanding is detected. Compared to all active methods, SFS has the smallest NDZ [29-32].

2.3.2.5 Sandia Voltage Shift

The sandia voltage shift (SVS) method is similar to the SFS method since both use positive feedback to detect islanding. In this method the inverter reduces its power and thus its voltage. It is only when the utility is disconnected, that voltage drops with a reduction of power at the PCC. This drop continues its way to reduce current and power output. As a consequence, a drop in the amplitude of V_{PCC} can be detected by UVP [33]. Similar to SFS, SVS has a small NDZ.

2.3.2.6 Frequency Bias or Active Frequency Drift (AFD) Method

Although the passive detection of islanded condition seems simple, it is not easy to set the threshold and detect blind spots. Henceforth, active methods are considered the key to solving islanding problems. Active methods include AFD, which is viewed as easy to implement with a PV power conditioner and a microprocessor based controller [34]. Moreover, the waveform of the current injected into the utility grid by the PV system is slightly distorted, which refers to the phase lag between the inverter output voltage and the voltage at the PCC. When islanding occurs, the frequency at the PCC will drift up or down augmenting the natural frequency [35].

Under islanded condition, the utility grid is disconnected and the local load is connected to the inverter output. In fact, if the connected load is resistive in nature, then the voltage response of this load is similar to the waveform current which is distorted. The current response of the inverter develops itself and completes the whole cycle of the utility voltage in time “t”. At that time, the inverter detects a distortion and induces a drift in the frequency to change the phase lag/distortion equal to zero. Distortion is well described by the chopping fraction (cf), which is a main parameter defined by the following equation:

$$cf = \frac{2T_Z}{T_{Vutil}} \quad (2)$$

T_{Vutil} is the period of utility voltage, and T_Z is the dead time

When the utility is connected, chopping fraction is the law. However, when the utility is disconnected a phase error occurs between two waveforms resulting in an increase in the “cf” [36-37]. Islanding happens when the”cf” value is greater than the threshold. In this method, the ADF's main advantages outweigh its disadvantages. It has a small NDZ compared to all other passive methods. The ADF is easy to install, as well as, having a very short detection time (< 2s). To conclude, the only weakness of AFD is its failure to cope and operate with multi inverter systems [38].

2.3.2.7 Current Injection Method

This method is an active islanding technique for a DR unit at the distribution voltage level [39]. Basically, the proposed method requires injecting a disturbance signal into the system via a direct axis (d-axis) or the quadrature axis (q-axis) current controllers using the three phase voltage-sourced converters (VSCs) as the interface unit [40]. In fact, the strategy of injecting signal through the d-axis controller modulates the amplitude of the voltage at the point of the common coupling (PCC). However, injecting signal via the q-axis controller results in a frequency deviation at the PCC, under islanded conditions. The reference and control signals are compared indicating an islanding condition. Hence, the advantage of this proposed method is that it enables detecting the islanding phenomena as fast as 33.3 ms for the parameter setting of the test system [41].The method is evaluated under the UL1741 anti-islanding test configuration. Finally, it is important to note that this method fails to detect islanding for loads having Q > 3 [42].

2.3.2.8 Negative-Sequence Current Injection Method

Islanding detection is demanded when utilizing DR units to prevent any accidental islanding [43]. Thus, another active method is introduced for islanding detection of DR units coupled to a utility grid through voltage–sourced converters

(VSC) [44]. This method is based on injecting negative sequence current through the VSC controller in order to detect and determine a negative sequence voltage at the PCC of the VSC using a unified three phase signal processor (UTSP). In fact, the UTSP can be described as an enhanced phase locked loop system using a high degree of noise isolation , that consequently leads to islanding detection based on injecting a small negative current (>3%) [45].This feasible method is best known for its accuracy especially for single DG units [46].

2.3.2.9 Q-*f* Droop Curve

The Q-*f* droop curve is a novel islanding detection method that relies on analyzing the reactive power versus frequency (Q-*f*) features between the DG and the islanded load. That is to say, this method equips the DG interface with the Q-*f* feature. During islanding, with a DG designed with zero reactive power, the system frequency will drift such that the load consumes zero Q. At the DG, the Q-*f* feature is represented by a linear function where the slope is adjusted to be steeper than the load curve such that the DG loses its stable operation during an islanding mode. Thus, for a DG equipped with the proposed Q-*f* feature, a simple detection method is sufficient for efficiently and accurately detecting islanding, as well as, maintaining a stable operation when tested under load switching, load imbalance and voltage sag conditions. This method showed accurate results under multiple DG operation [47].

2.3.3 Hybrid Detection Techniques

The hybrid method is a combination of both active and passive methods. It is used to overcome obstacles caused by Active and Passive method. Thus, it involves two stages in the detection process. In the first stage, a hybrid method begins with the passive method to ensure primary protection. The second stage occurs when islanding is suspected so that active method is implemented to detect islanding [48]. The flow chart of the hybrid technique is shown in Figure 5.

2.3.3.1 Technique Based on Positive Feedback (PF) and Voltage Imbalance (VU)

A technique based on PF and VU is one of the hybrid techniques that uses both PF (active technique) and VU (passive technique) [49]. The purpose is to track the three phase voltages during the whole process to determine the VU as shown in the equation below (3):

$$VU = \frac{V_{+Sq}}{V_{-Sq}} \quad (3)$$

V_{+Sq} and V_{-Sq} are the positive and negative sequence voltage, respectively.

During load change, islanding, and switching action, voltage spikes will be monitored. Once the VU spike gets above a set value, a frequency set point of the DG is changed, which will result in a change in the system frequency.

2.3.3.2 SFS and ROCOF Method

In this hybrid technique, both SFS and ROCOF methods are used. SFS, which is the optimized sandia frequency shift, is the active method, and the ROCOF; which is the rate of change of frequency relay, are interlinked [50]. It implies that, the SFS method gets activated only when an islanding condition is detected by the ROCOF relay, which discerns any variation in df/dt. In the case of a disturbance, a trip signal will be sent to a multiple switch, which consequently activates the SFS signal. This method provides an efficient discrimination between the load switching conditions and the islanded condition, causing false trips prevention. Moreover, the proposed method improves the steady state power quality of the system.

2.3.3.3 Technique Based on Voltage and Real Power Shift

This technique is based on using both passive and active techniques. In fact, it depends on utilizing the average rate of the voltage change (passive technique) and a real power shift (active technique) to surpass the limitations of passive and active techniques when detecting islanding [51]. This method looks advantageous, as it enables islanding detection with multiple DG units operating at unity power factor.

2.3.3.4 Hybrid SFS and Q-*f*

Combining slip mode frequency shift (SMS) with reactive power versus frequency (Q-*f*) as the active methods, is a novel hybrid method in islanding detection. This is based on forcing the DG to lose its stability and drift its frequency out of the permitted range of frequency relays [52]. Then an under/ over frequency protection relay, as a passive method, is sufficient to detect the islanding.

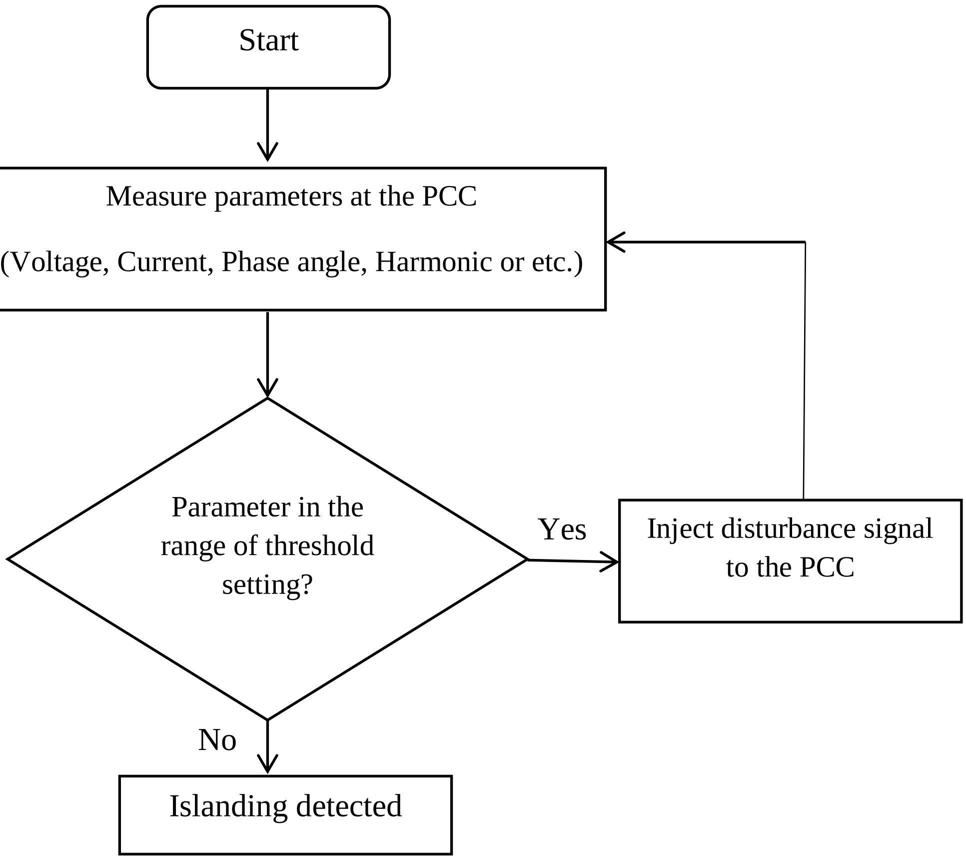

Figure 5: Flow chart describing the process of a hybrid islanding detection

2.4 Comparison of Islanding Detection Techniques

The following table highlights islanding detection techniques together with their advantages and disadvantages.

Table 1: Comparison of islanding detection techniques

Islanding Detection Techniques	Advantages	Disadvantages
1. Remote Techniques	• Highly reliable	• Expensive to implement
2. Local Techniques		
a) Passive	• Short detection	• Difficult to detect

	time • Does not perturb the system	islanding when load and generation in the islanded system closely match • Special care has be taken while setting the threshold
b) Active	• Small NDZ	• Introduces perturbation in the system • Perturbation often degrades the power quality
c) Hybrid	• Small NDZ • Perturbation is introduced only when islanding is suspected	• Islanding detection time is prolonged • Both passive and active techniques are implemented

2.5 Islanding Detection for Micro-grids

Unlike the previously studied methods used in islanding detection that work mainly in the connected mode, innovative islanding detection tools are in place to perform in both connected and disconnected mode. In fact, a novel islanding detection method for micro-grids is capable of successfully operating in both modes. This research highlights three useful techniques: Variable Impedance Insertion Method, Grid Impedance Estimation Method, and Harmonic Signature. Although micro-grids have numerous positive features that act as a reliable protection scheme for the load during abnormal events or spikes, it is still not a common practice yet [53].

2.5.1 Variable Impedance Insertion Method

An innovative islanding detection method is suggested based on the insertion of a large impedance at the low voltage side of the grid. In accordance with the micro-grid central switch, this method uses a smart hybrid automated transfer switch (HATS) with an incorporated IDM factor [54]. The HATS monitors the operational mode of the micro-grid and coordinates the operation of the switch. The importance of this method is its ability to provide a reliable indicator for the operational mode of the micro-grid through measuring current of the inserted impedance compared with the current via the HATS. The testing circuit of the variable impedance insertion detection method is shown in Figure 6.

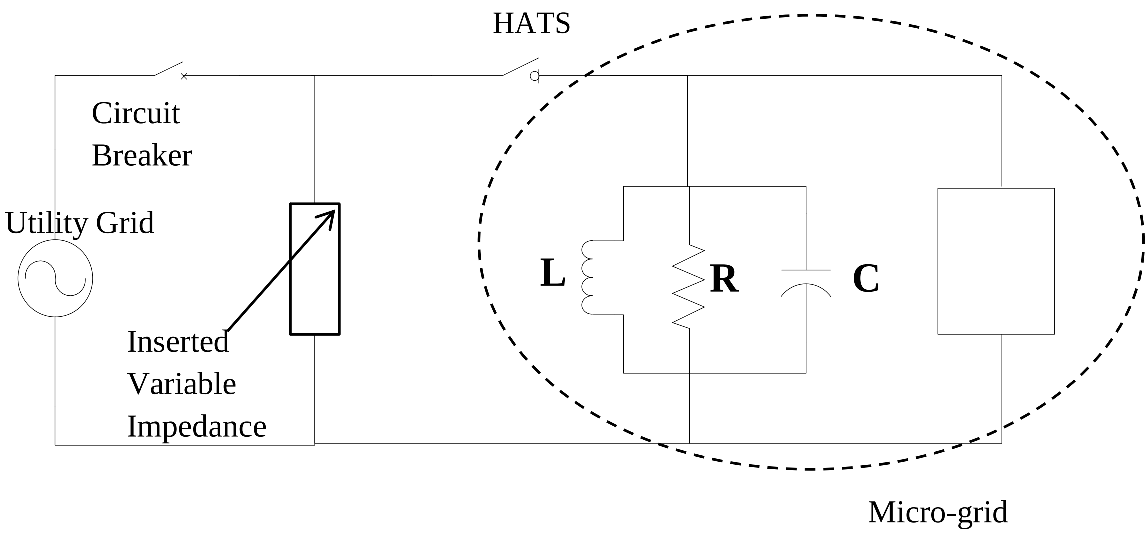

Figure 6: Variable Impedance insertion islanding detection method testing Circuit

2.5.2 Grid Impedance Estimation Method

Another islanding detection method that is highlighted in the research is grid impedance estimation, where the VSI will be in islanded mode if the Z_g(Z_g <1.75Ω) changes more than 0.5 Ω in 5s [55]. Grid impedance estimation operates in both islanded and grid-connected mode. Therefore, it has two main structures .The first being, the grid parameter estimation that is responsible for calculating the amplitude, magnitude, grid phase, and frequency. Second, all these parameters can be operated by an adoptive droop controller to be later injected into both the active and reactive power by the VSI.

2.5.3 Harmonic Signature

Another passive method capable of detecting islanding at a low cost and in effective way is Harmonic Signature [56]. It belongs to passive islanding detection, but it is based mainly on the fifth harmonic voltage magnitude at the PCC between grid-connected and islanded modes of operation and can detect islanding within the NDZ. The Harmonic Signature method operates in both grid-connected and disconnected mode. First, it measures the three-phase voltages (V_a, V_b,and V_c). Then, it decomposes the voltage harmonics to calculate the fifth harmonic voltage. When that happens, it automatically compares the fifth harmonic voltage with the V threshold. Islanded mode occurs only if the fifth harmonic voltage is greater than threshold voltage. Otherwise, there is no islanding as shown in Figure7.

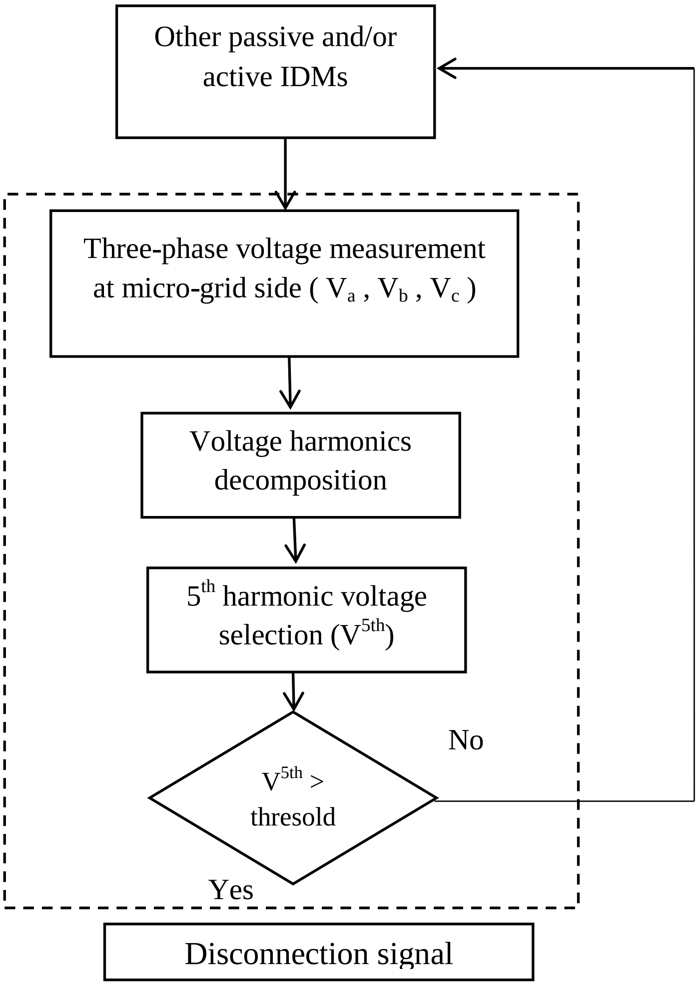

Figure 7: Flow chart of the harmonic signature method

Chapter 3: Islanding Detection using Droop Control

This chapter includes a deep and detailed description of the droop control method and, compares with the newly proposed islanding detection of the micro-grid method using modified droop control while operating with both single and multiple DGs. It also provides a clear image of the system studied for this thesis.

3.1 Droop Control Method Background

Micro-grids contain different kinds of DGs that all have to be under total control to maintain equal power sharing for regulating voltage amplitude and frequency, otherwise power mismatching can occur causing serious problems. Such requirements impose many challenges to keep power production under control. Thus, a common communication technique is used to track the voltage amplitude and the frequency, as well as, balance the power sharing among all the DGs the entire time. However, this does not seem to be feasible or reliable for one reason or another [57]. Thus, a non-communication technique is required to enable continuous and reliable tracking that allows every unit to regulate output voltage and frequency. This technique uses a method of frequency and voltage droop similar to conventional power system generators [58]. The droop control method is widely popular, in the meantime it ensures power sharing and coordinated voltage and frequency regulation in micro-grids. It is a control strategy applied to generators for primary frequency and voltage control allowing parallel generator operation such as load sharing. This proposed control scheme has been verified to work successfully in both the islanded and grid-connected modes. Droop control method is characterized by its ease of implementation, use of local voltage and current information, accommodating operation in the grid-connected mode, and the plug-and-play operation of the DG systems [59].

3.2 Frequency and Voltage Droop Equations

The power flows into a line at point A, as shown in Figure 8, is expressed as [60]:

$$\bar{S} = P + jQ = \bar{V}_1 I^* = V_1 \left[\frac{\bar{V}_1 - \bar{V}_2}{\bar{Z}}\right]^* = V_1 \left[\frac{V_1 - V_2 e^{j\delta}}{Z e^{-j\theta}}\right] = \frac{V_1^2}{Z} e^{j\theta} - \frac{V_1 V_2}{Z} e^{j(\theta+\delta)} \quad (4)$$

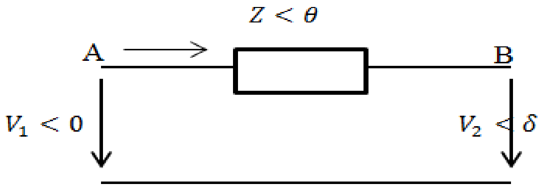

Figure 8: Power flow through a line

Active and reactive power flowing into the line is described as:

$$P = \frac{V_1^2}{Z}\cos\theta - \frac{V_1 V_2}{Z}\cos(\theta + \delta) \quad (5)$$

$$Q = \frac{V_1^2}{Z}\sin\theta - \frac{V_1 V_2}{Z}\sin(\theta + \delta) \quad (6)$$

With $e^{j\theta} = R + jX$, (5) and (6) are rewritten as :

$$P = \frac{V_1}{R^2 + X^2}\left[R(V_1 - V_2\cos\delta) + XV_2\sin\delta\right] \quad (7)$$

$$Q = \frac{V_1}{R^2 + X^2}\left[-RV_2\sin\delta + X(V_1 - V_2\cos\delta)\right] \quad (8)$$

Or

$$V_2\sin\delta = \frac{XP - RQ}{V_1} \quad (9)$$

$$V_1 - V_2 \cos\delta = \frac{RP + XQ}{V_1} \quad (10)$$

For overhead lines where X >> R, then R can be ignored. If the power angle δ is also small, then equation (9) and (10) can be simplified further by using the approximations sin δ = δ and cos δ = 1. Equations (9) and (10) then become:

$$\delta = \frac{XP}{V_1 V_2} \quad (11)$$

$$V_1 - V_2 = \frac{XQ}{V_1} \quad (12)$$

For *X* >> *R*, a minimal power angle δ, and a small voltage difference *of* $V_1 - V_2$, equations (11) and (12) demonstrate that the power angle depends mostly on *P*, while the voltage difference depends largely on *Q*. That is to say, the angle δ can be controlled by modifying *P*, and the inverter voltage V_1 *is* controlled through *Q*. As a consequence, when P and Q are known, the frequency and amplitude of the grid can be determined. In conclusion, the frequency and voltage droop equation is formed [61]:

$$f - f_0 = -m_p(P - P_0) \quad (13)$$

$$V_1 - V_0 = -n_q(Q - Q_0) \quad (14)$$

f_0 and V_0 are the nominal frequency and the nominal grid voltage, respectively, and P_0 and Q_0 are the set points for active and reactive power of the inverter, respectively. The frequency and voltage droop control features are demonstrated graphically in Figure 9 [62].

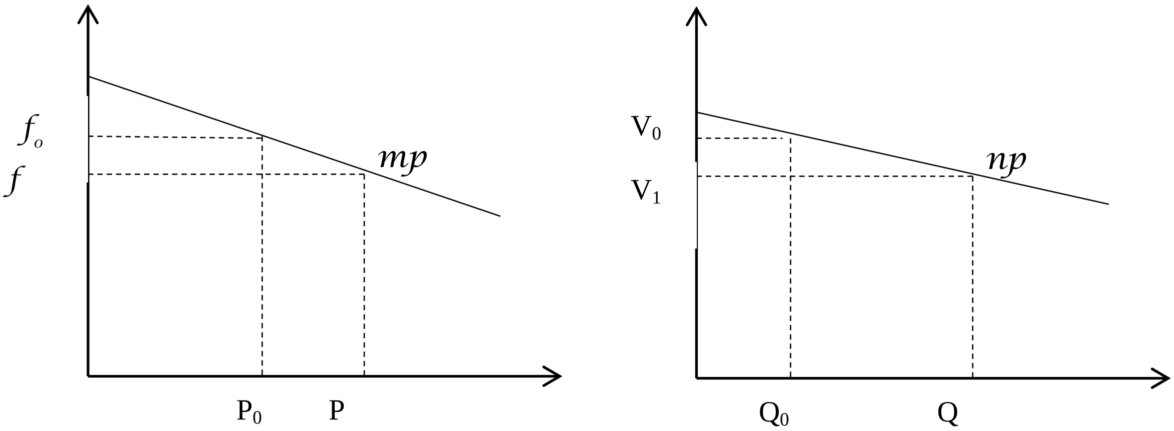

Figure 9: Frequency and voltage droop control characteristics

3.3 Proposed Islanding Detection Method of Micro-Grids

This research studies how to use the droop gain value for islanding detection and proposes an efficient islanding detection for micro-grids through modifying the droop gain value adopted from the frequency droop equation. This proposed detection method relies on adaptively modifying the droop slope such that the droop gain value prior to islanding creates instability using mp2, which is an unstable droop gain value. Therefore, if the value of the frequency and voltage violate the threshold value, which varies between 59.3Hz to 60.5Hz and 0.88V to 1.1V, respectively, then an islanded condition occurred .Once islanding is detected, the droop gain adaptively changes to mp1, which is a stable droop gain value, to stabilize the voltage and frequency of the micro-grid within the IEEE Standard threshold value as states above. From previous studies, it is known that high values of mp can lead to micro-grid instability while low mp values can stabilize the system [63]. To identify the values of the droop gains (to be used for grid connected and islanded operation), repeated dynamic simulation was conducted to identify mp1 and mp2. This is demonstrated in the following flow chart in Figure 10.

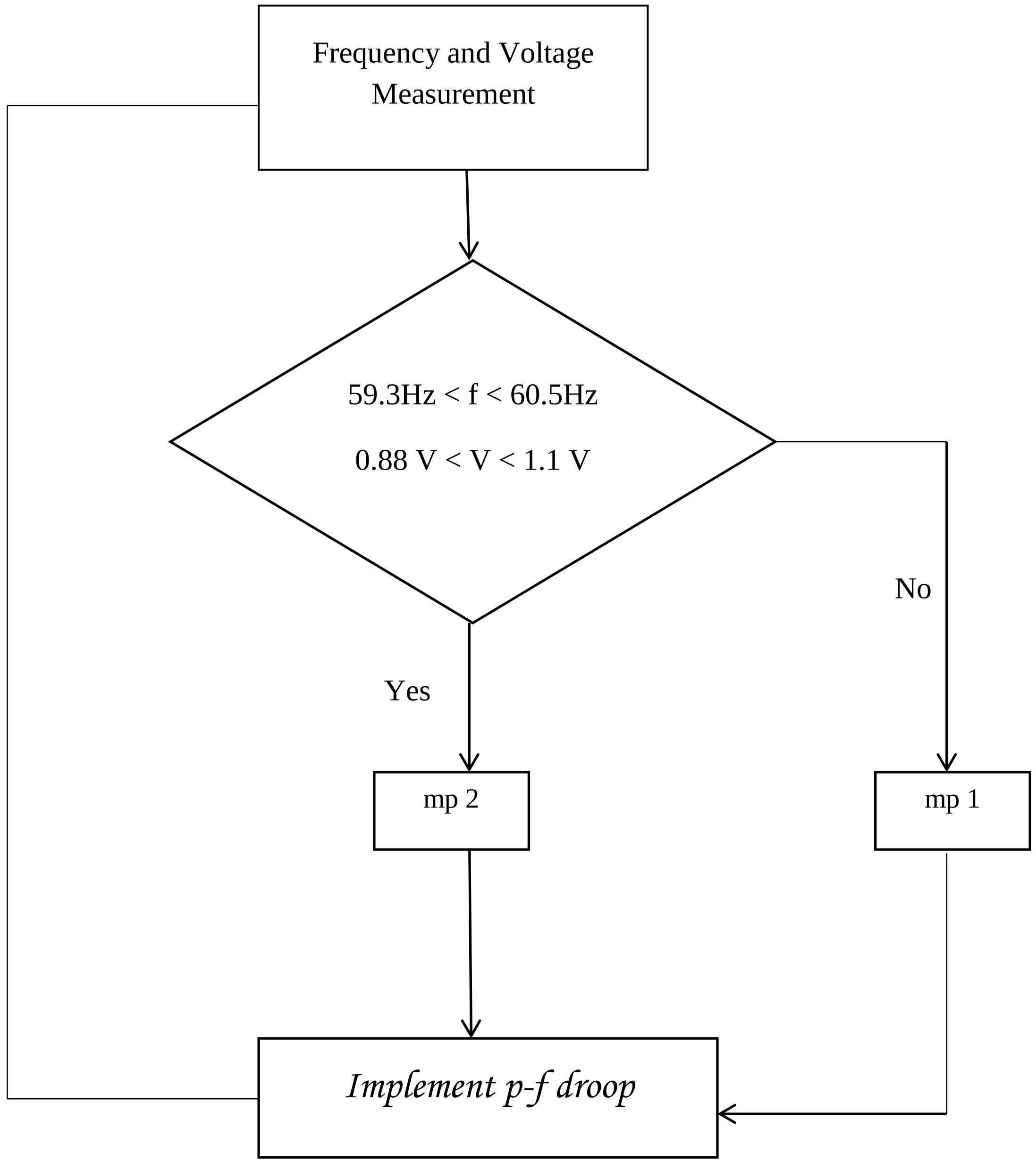

Figure 10: Flow chart of the proposed method

3.4 Modeling of the System under Study

This research introduces a system that performs distribution levels in order to detect islanding in micro-grids. The system under study is classified into two models one being single and the other multiple DGs. A brief description of the PSCAD/EMTDC models of the used system for this study is given in this section.

3.4.1 Single DG Model

The system of a single DG is simply presented first as a single line diagram and then labeled in details with PSCAD/EMTDC implementation model, as shown in Figure 11 and 12, respectively. Details about the system model, DG, and load parameters are provided in table 2. It consists of one inverter based DG rated at 100 kW operating at 480 V. The DG is equipped with two droop controls namely the P-f and Q-V droop. The Q-V droop is designed as the DG injects zero reactive power at 1 p.u voltage. The grid is modeled as a voltage source behind impedance, and the load is modeled as an RLC load where the load parameter values varied to simulate various active and reactive power mismatch cases. The interface control, presented in Figure 13, is designed to control the active and reactive power output of the DG. As in Figure 13, the DG active and reactive power output (Pinv and Qinv) are measured and compared to the active and reactive power reference values (Pset and Qset). Typically, in islanding detection studies, Pset is fixed to the DG rated output power while Qset is set to zero such that the DG operates at unity power factor. For micro-grids, this is not the case where the active and reactive power set points are determined based on a droop control as indicated in Figure 14. The two droop equations can be expressed as follows:

$$\left(V_{pu-measured} - 1\right) * \frac{G}{1 + sT} * -np = Q_{set} \quad (15)$$

$$(f_{measured} - 60) * \frac{G}{1 + sT} * mp + 0.1MW = P_{set} \quad (16)$$

As seen from the equations, the active and reactive power set points are dependent on the measured voltage and frequency. From Figure 13, the errors in active and reactive power are passed to a proportional, integral controller (PI controller) to generate the d-q axis current reference points, which are compared with the DG output current. The error in the current is then passed to another PI controller to generate the dq axis voltage reference values. The voltage reference points are utilized to determine the modulation index (m) and the modulation signal angle (theta). As seen in Figure 15, the amplitude and angle of the modulation signal are compared with a high frequency triangular waveform to generate the inverter switching signals.

As seen in Figure 14, the proposed islanding detection method measures both the frequency and voltage and compares them with threshold values. The method is equipped with two droop gain values that are interchanged depending on the voltage and frequency deviations. The first droop gain (mp2) guarantees that the micro-grid is stable while connected to the grid and unstable as soon as the micro-grid is disconnected from the utility. The normal operation droop gain will guarantee that either the frequency or voltage will deviate beyond the IEEE Std. 1547 threshold values. Once autonomous micro-grid operation is detected, the droop gain adaptively changes to the value of (mp1), which is the droop gain value that stabilizes the voltage and frequency of the micro-grid within the IEEE Standard threshold values that vary between 0.88 V to 1.1 V and 59.3 Hz to 60.5 Hz, respectively. The proposed micro-grid transition method is presented in Figure 10.

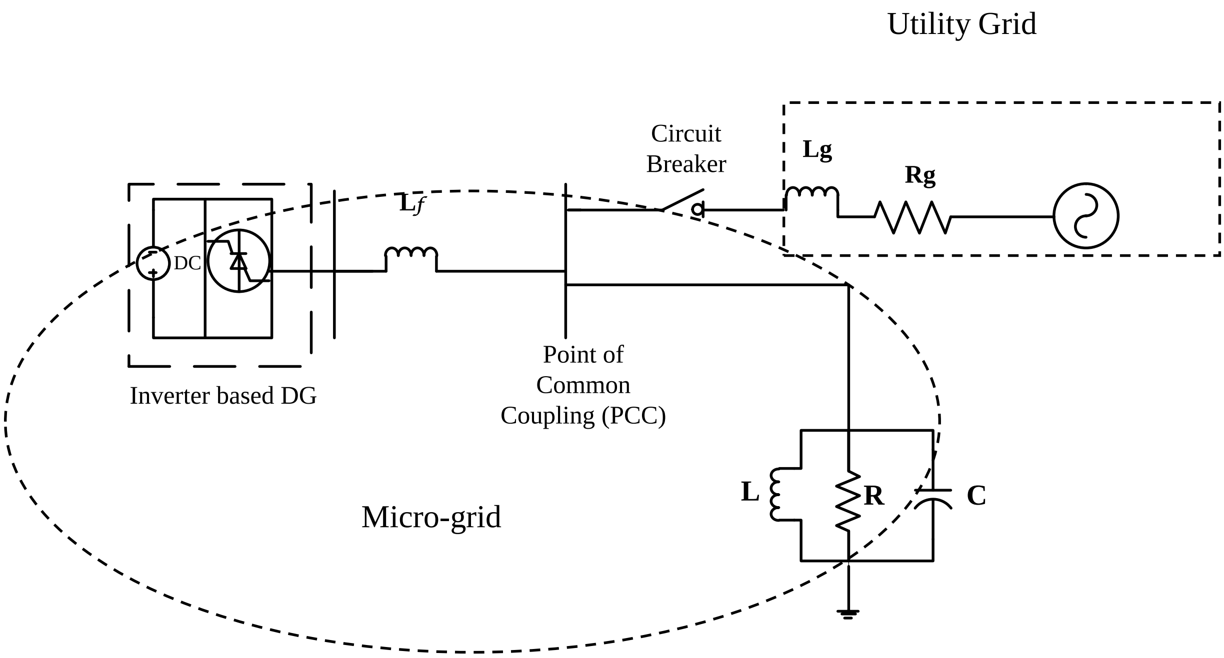

Figure 11: Single line diagram of single DG system under study

Table 2: System, DG, and load parameters of single DG

Single DG		
Grid Parameters		
Voltage (line to line)	480V	
Frequency	60Hz	
Grid Resistance	0.02Ω	
Grid Inductance	0.3mH	
DG Inverter Controller Parameters		
kp' = 5	kI = 0.07	
kp = 8	kI = 0.08	
Pref = 0.1Mw	Qref = 0Mvar	
Load Parameters		
R(Ω)	L(H)	C(μF)
1.152	0.00345	2037

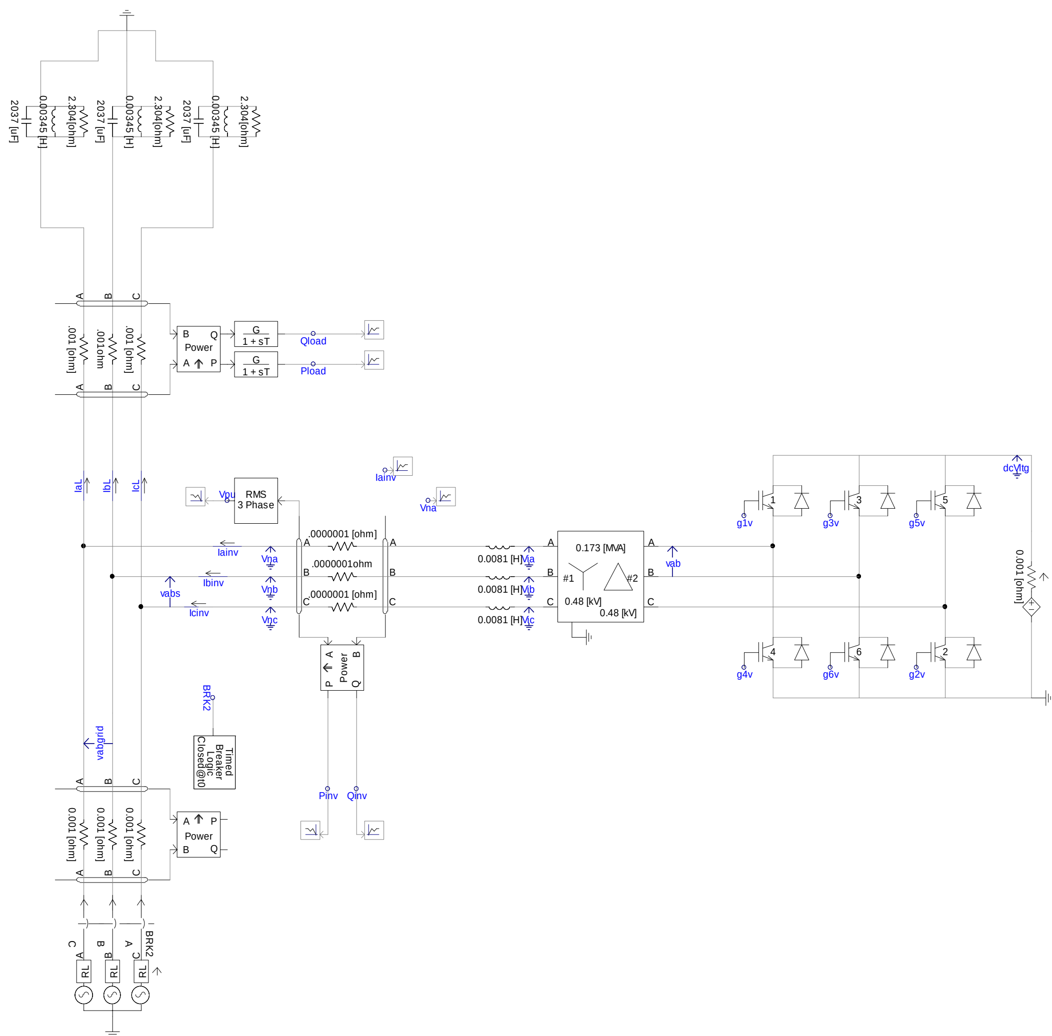

Figure 12: System under study with single inverter based DG PSCAD/EMTDC model

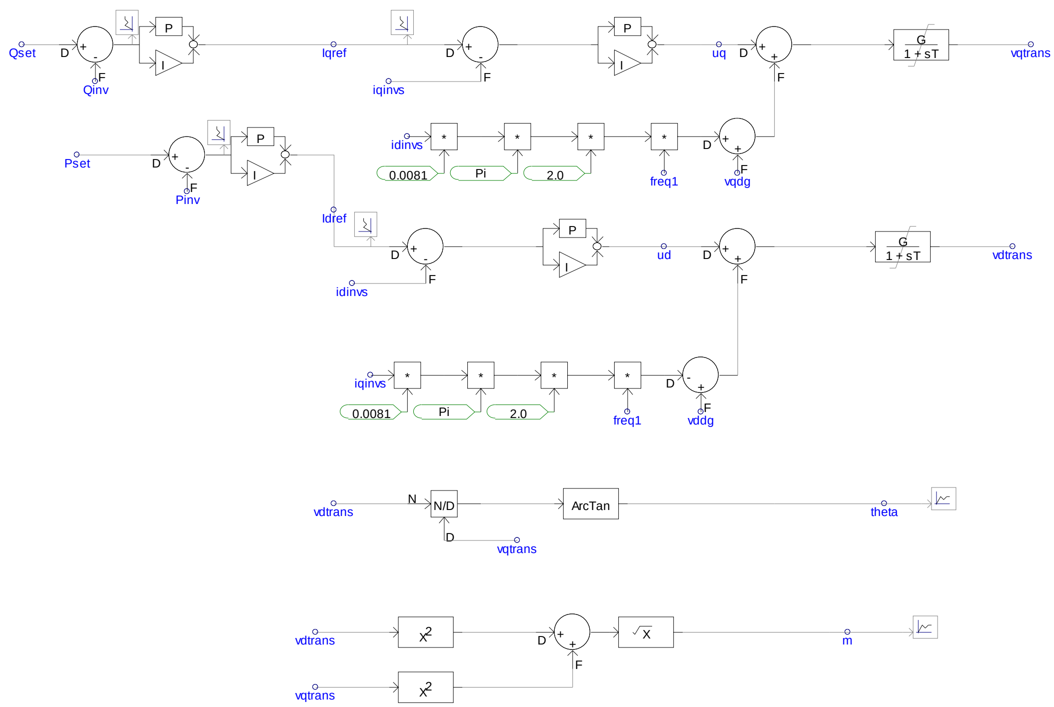

Figure 13: Interface control for inverter based DG

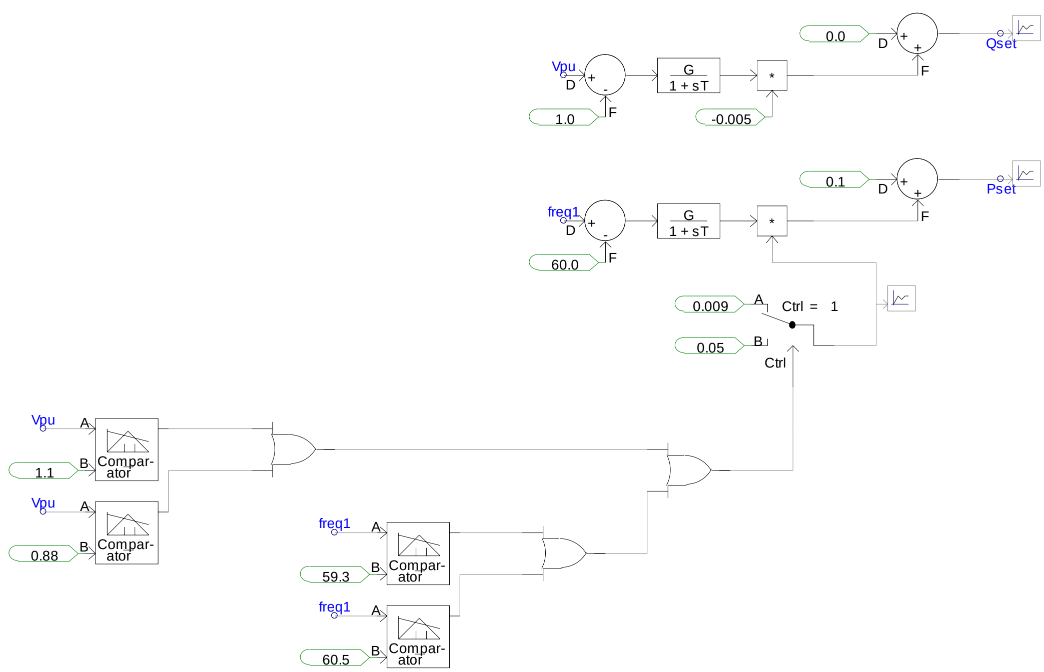

Figure 14: Droop control including the proposed islanding detection technique

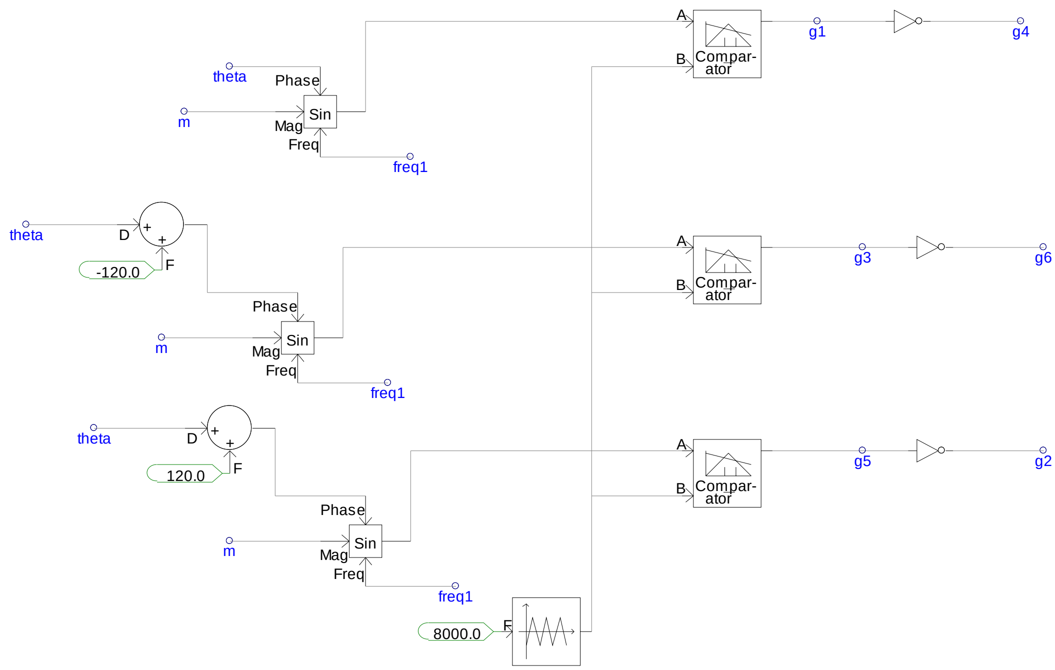

Figure 15: Sinusoidal pulse width for generating inverter switch

3.4.2 Multiple DG Model

The multiple DG model looks similar to the single DG model, but it contains one extra DG rated at 100 kW operating at 480 V. Figures 16 to 20, highlight the followings:

- Single line diagram
- PSCAD developed model for the system under study
- Interface control for Inverter Based DG
- Droop Control including the proposed islanding detection technique
- Sinusoidal Pulse Width for Generating Inverter switch

Details about the system model, DG, and load parameters are provided in table 2.

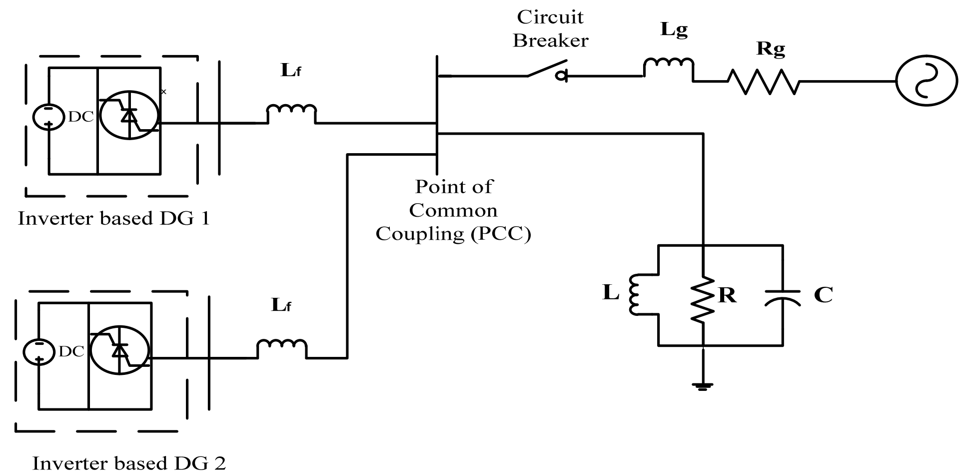

Figure 16: Single line diagram of multiple DGs system under study

Table 3: System, DG, and load parameters of multiple DGs

Multiple DGs		
Grid Parameters		
Voltage (line to line)	480V	
Frequency	60Hz	
Grid Resistance	0.02Ω	
Grid Inductance	0.3mH	
DG Inverter Controller Parameters		
kp' = 5	kI = 0.07	
kp = 3	kI = 0.08	
Pref = 0.1Mw	Qref = 0Mvar	
Load Parameters		
R(□)	L(H)	C(µF)
2.304	0.00345	2037

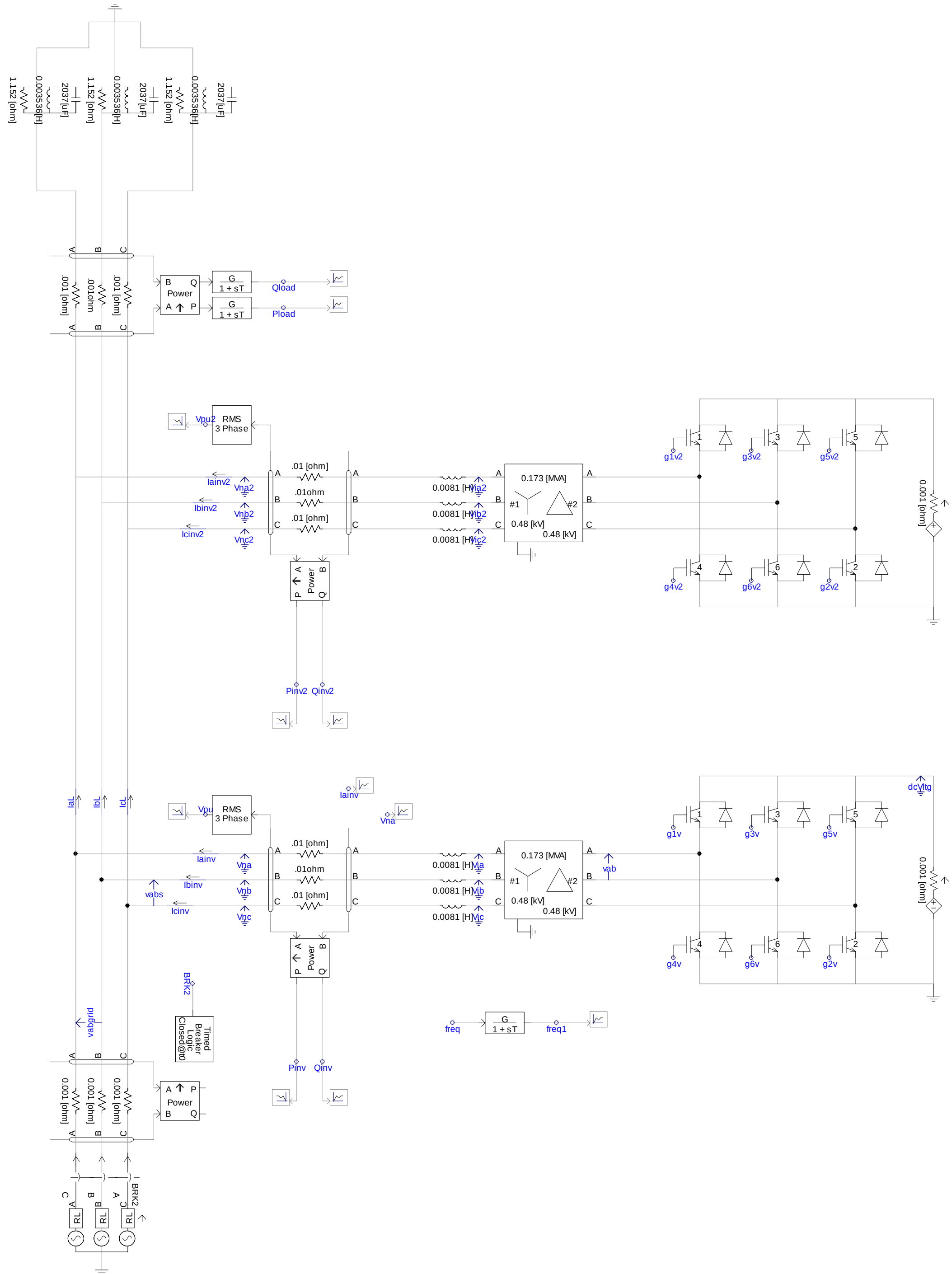

Figure 17: System under study with two inverter based DG PSCAD/EMTDC model

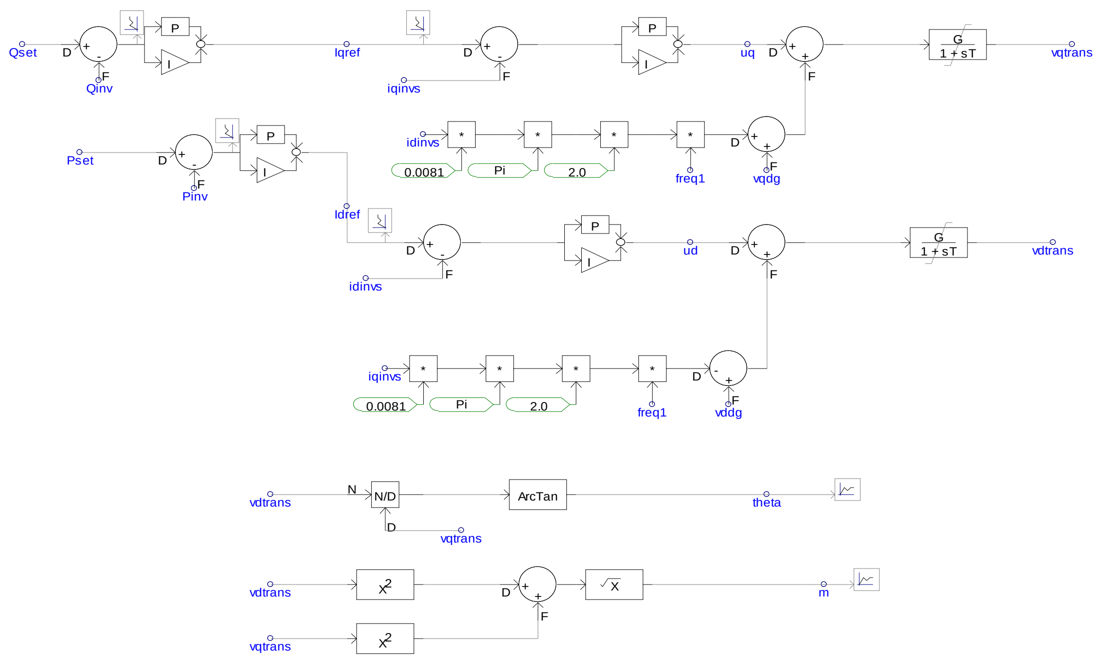

Figure 18: Interface control for inverter based DG for multiple DGs

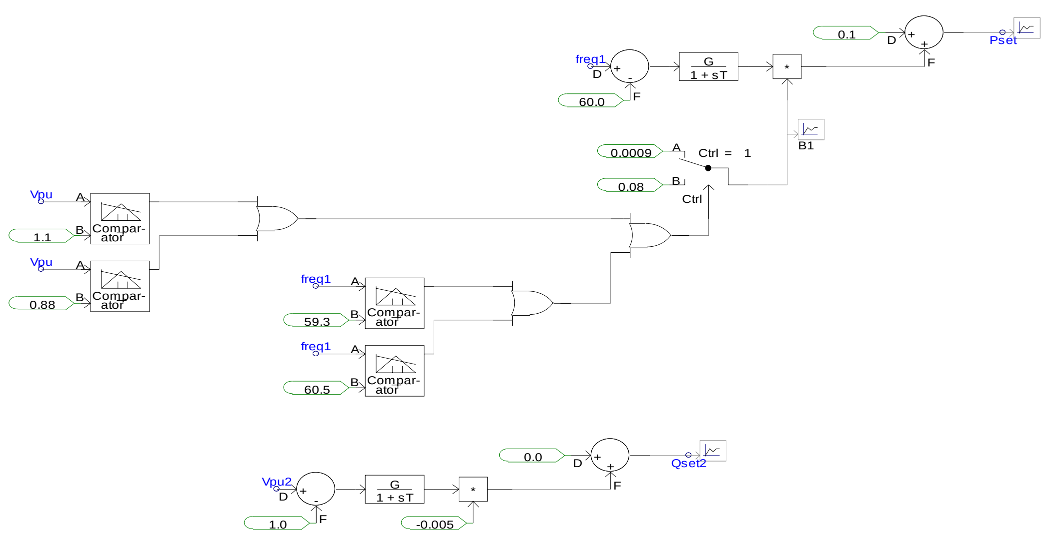

Figure 19: Droop control including the proposed islanding detection technique for multiple DGs

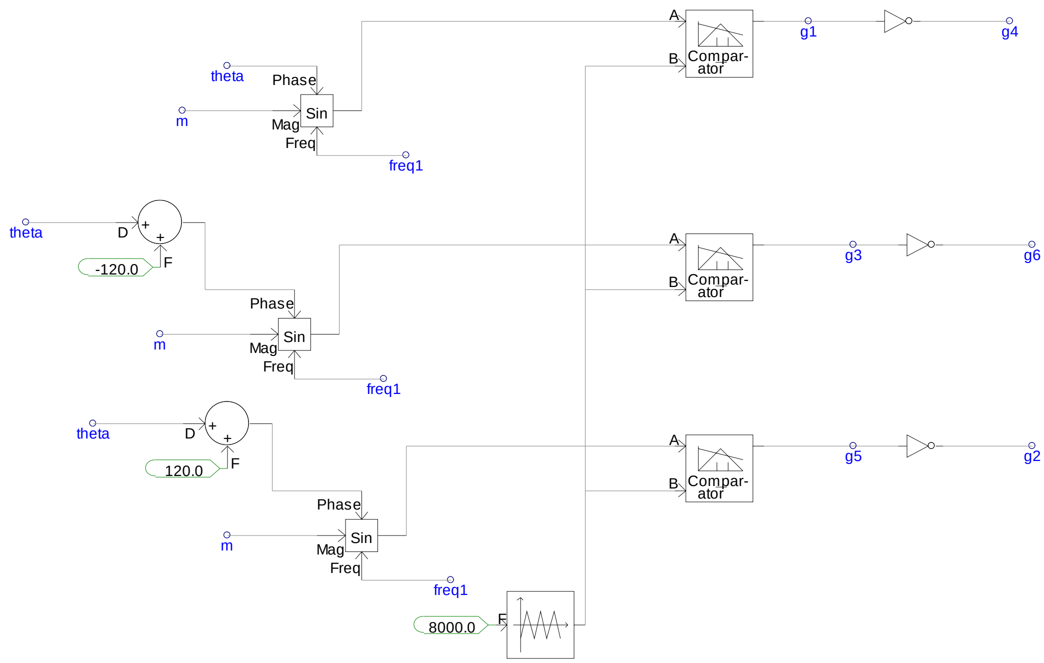

Figure 20: Sinusoidal pulse width for generating inverter switch for multiple DGs

3.4.3 Single DG Operation

To detect islanding, it was necessary to track active power mismatch in order to find out if the proposed method is efficient and reliable. To address that, the power value has been altered by adding ±10% and ±20% simultaneously to the main power value P=100 kW in accordance with resistance variations R =2.304. Table 4, includes the load parameters for different values of P.

Table 4: Load parameters for different values of P for single DG

P (kW)	**R (Ω)**	**L (H)**	**C (μf)**
120	1.92	0.00345	2037
110	1.772307692	0.00345	2037
100	2.304	0.00345	2037
90	2.56	0.00345	2037
80	2.88	0.00345	2037

Furthermore, reactive power mismatch has been studied to ensure its effect on islanding detection. The active power mismatch is approximately set to zero, and the load is adjusted to create a reactive power mismatch that corresponds to load resonance frequencies within the range of 59.3 and 60.5 Hz. Table 5, includes the load parameters for different values of the frequency.

Table 5: Load parameters for different values of *f* for single DG

f (Hz)	**R (Ω)**	**L (H)**	**C (μf)**
60.5	2.304	0.003397	2037
60.25	2.304	0.003426	2037
60	2.304	0.00345	2037
59.5	2.304	0.003512	2037
59.3	2.304	0.003536	2037

While experimenting with the variation on both active and reactive power mismatch, fluctuations have been observed. Once islanding conditions happen at t = 3 s, the DG operation becomes unstable and the frequency deviates and exceeds the threshold values f = 59.3 and 60.5 Hz. Thus, the proposed method's main task is to maintain stability in any condition by changing the gain value of the droop from an unstable to a stable one.

3.4.4 Multiple DG Operation

Islanding detection method is required to test other alternatives to ensure reliability. Thus, another model is introduced that consists of multiple DG operation similar in performance to the single DG operation, but different in parameter specifications. In order to reach that, the active power of the load was adjusted such that the active power mismatch is ±10% and ±20% while the reactive power mismatch is adjusted to approximately zero. Table 6, describes the load parameters for different values of P.

Table 6: Load parameters for different values of P for multiple DGs

P (kW)	R (Ω)	L (H)	C (µf)
220	1.047272727	0.00345	2037
210	1.097142857	0.00345	2037
200	1.152	0.00345	2037
190	1.212631579	0.00345	2037
180	1.28	0.00345	2037

Equally important, reactive power mismatch has been again highlighted to test its impact on islanding detection. Table 7, illustrates the load parameters for different values of the frequency.

Table 7: Load parameters for different values of *f* for multiple DGs

f (Hz)	**R (Ω)**	**L (H)**	**C (µf)**
60.5	1.152	0.003397	2037
60.25	1.152	0.003426	2037
60	1.152	0.00345	2037
59.5	1.152	0.003512	2037
59.3	1.152	0.003536	2037

While testing active and reactive power mismatch, changes have been observed. Once transition conditions happen at t = 5 s, the DG operation becomes unbalanced and the frequency deviates and exceeds the threshold values f = 59.3 and 60.5 Hz.

Chapter 4: Simulation Results and Discussions

This chapter simulates two models for testing the reliability of the proposed method in order to ensure its effectiveness and feasibility one being the DG and the other multiple DGs. Each model is labeled, tested and examined separately under different conditions. The simulation results that include the voltage, frequency, active and reactive power outputs for different conditions are presented.

4.1 Single DG Simulation Results

The system for single DG was studies and tested to be as basis for further analysis having the commonly known characteristic of the frequency resonant level of 60Hz and active power P= 100 kW. All condition parameters, whether frequency, voltage, active power, and reactive power were imbalanced just after islanding took place at t = 3 s. Thus, a series of conditions were proposed in order to ensure and prove that imbalanced loads can still occur at any permissible frequency variations. The proposed method, which is micro-grid islanding detection, tested all suggested conditions which were put under different frequencies from 59.3Hz to 60.5Hz while power variations at different values of ±10% and ±20%.

4.1.1 Case 1: Zero Active and Reactive Power Mismatch

The worst case for islanding detection is studied here, which is zero active and reactive power mismatches. It occurs when active and reactive power of the RLC load is equal or closely matches the active and reactive power of DG active and reactive power. Figure 21, illustrates the simulation result of the worst case of islanding when P=100 kW and f = 60 Hz with and without the proposed method.

Without proposed method, when islanding occurs frequency and voltage will not exceed the threshold value, however, with the proposed method, the transition was detected at t = 3.513 s when the frequency variation violated the standard permissible level. After the detection of the island, all the parameters became stable.

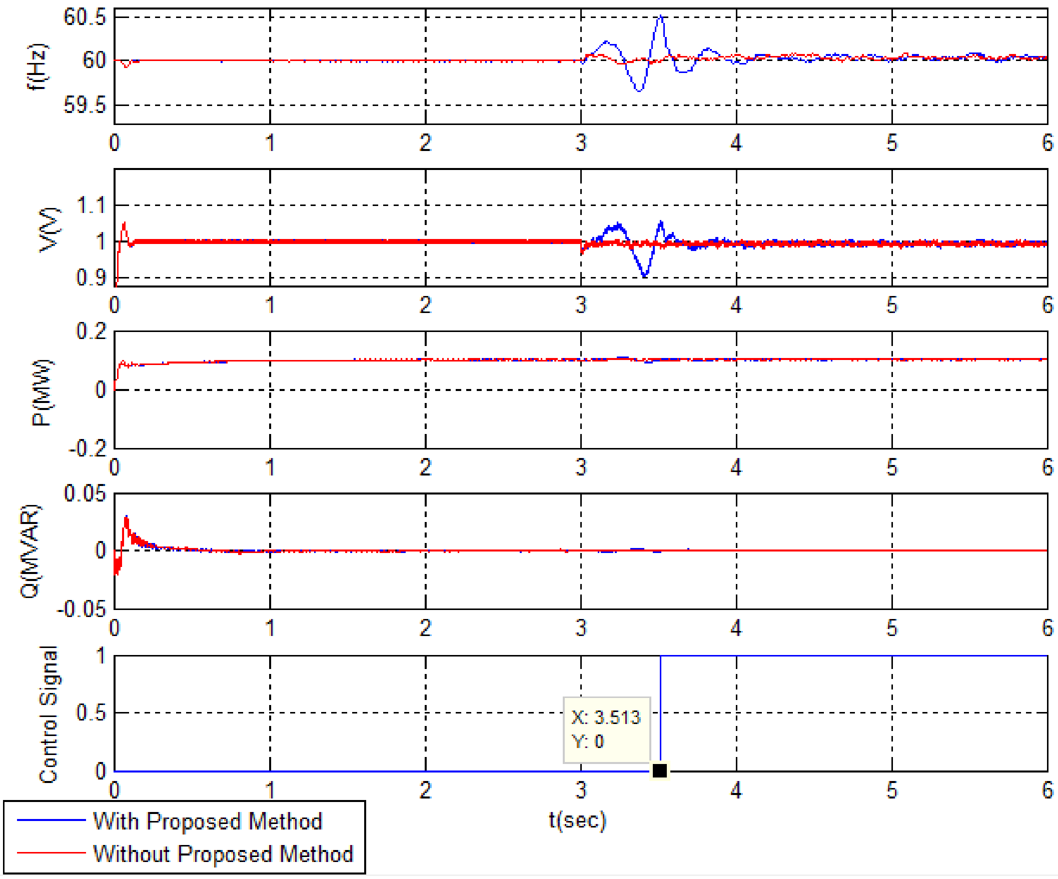

Figure 21: Frequency, voltage, active and reactive power for the 100 kW loading condition

4.1.2 Case 2: Active Power Mismatch

The active power mismatch can be defined as the difference between the load active power and the DG active power .Based on IEEE 1547 standard, the active power mismatch was tested at different active power values of ±10% and ±20%.

Figures 22 and 23, show two conditional results based on the ±10% active power mismatch between the load and the DG being , P=110 kW and P=90 kW respectively. When the islanding occurs at t = 3 s the frequency drops to its lower threshold limits which is less than 59.3 Hz. At that moment, the islanding is detected using the proposed method and the parameters become stable.

- *Condition 1: P = 110 kW, f = 60 Hz*

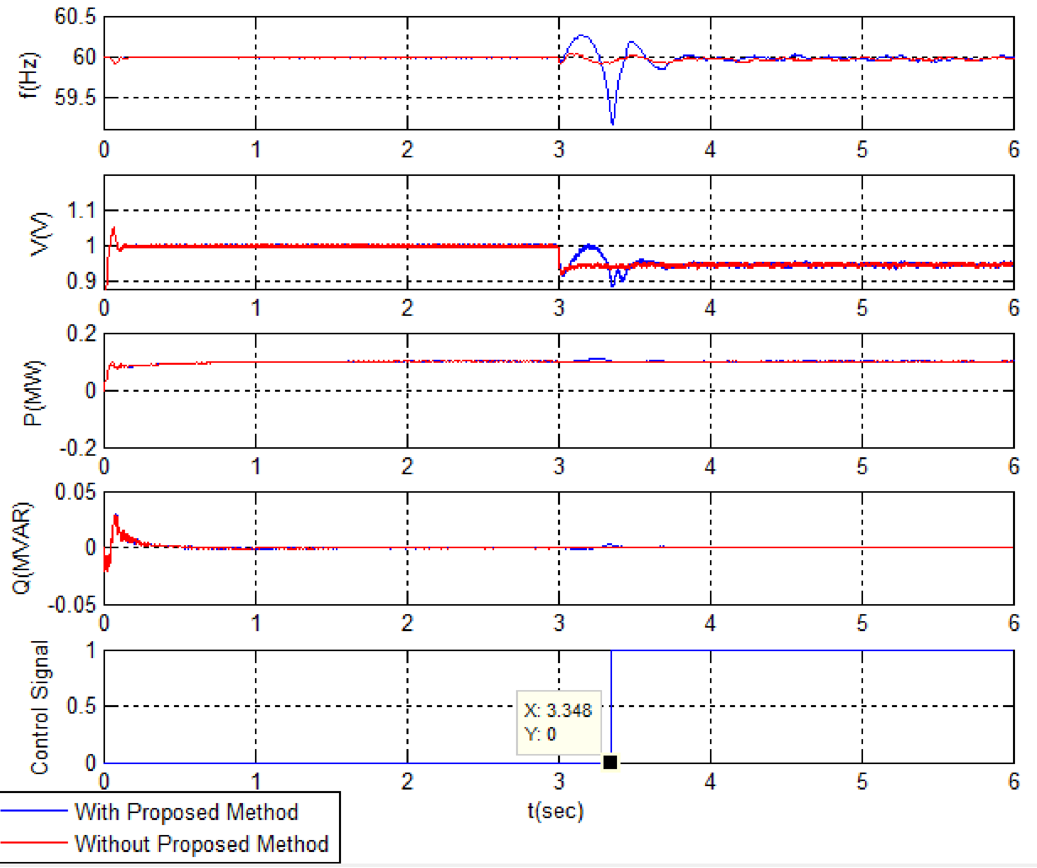

Figure 22: Frequency, voltage, active and reactive power for the 110 kW loading condition

- *Condition 2: P = 90 kW, f = 60 Hz*

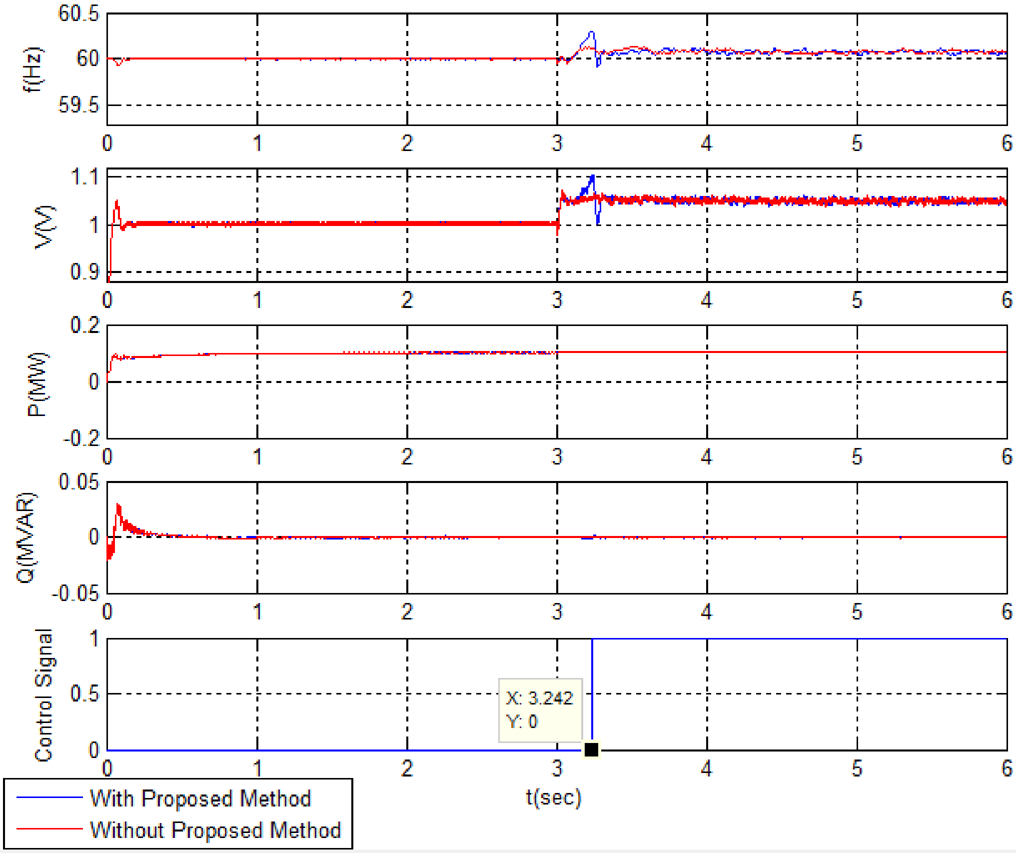

Figure 23: Frequency, voltage, active and reactive power for the 90 kW loading condition

Figures 24 and 25, illustrate the simulation results of Condition 3 and Condition 4, which are ±20% active power mismatch between the load and the DG. During the islanding event the voltages violate the permissible value. Then, the proposed method detects the transition and returns all the parameters to the original values before islanding.

- *Condition 3: P = 120 kW, f = 60 Hz*

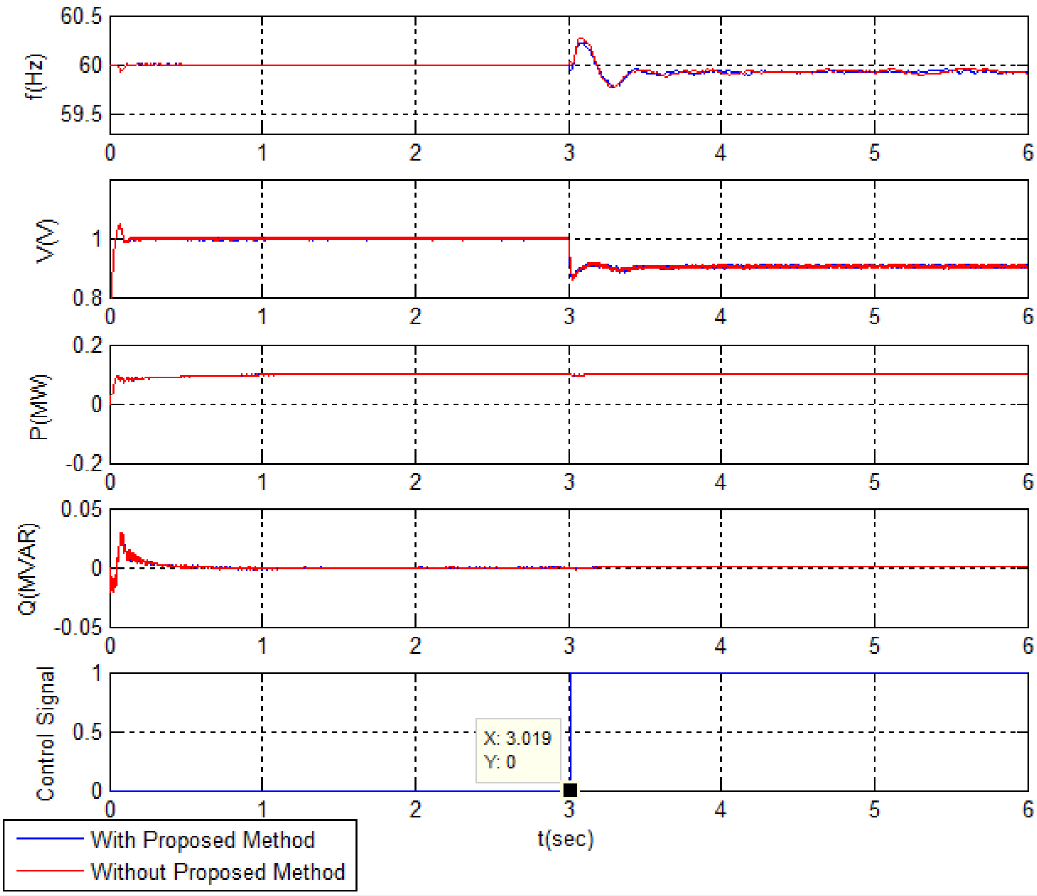

Figure 24: Frequency, voltage, active and reactive power for the 120 kW loading condition

- *Condition 4:   P = 80 kW, f = 60 Hz*

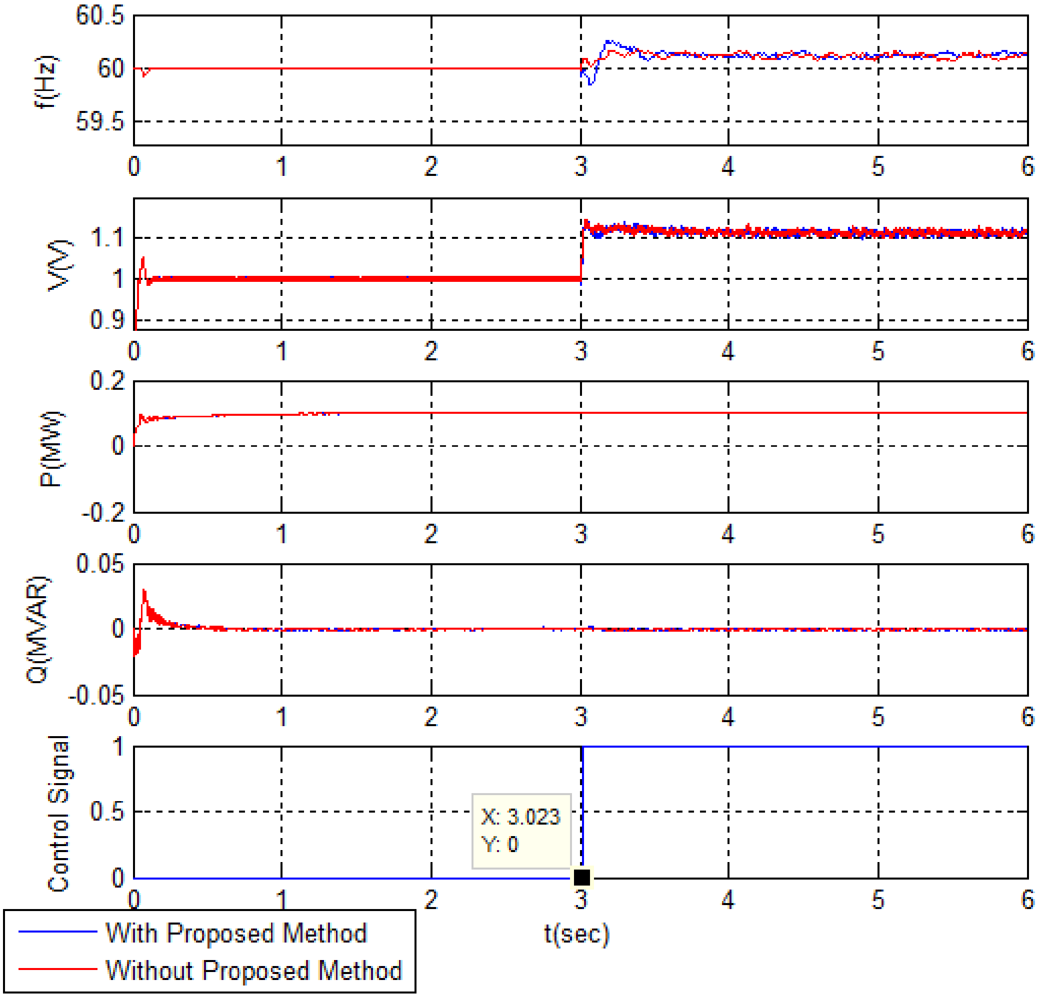

Figure 25: Frequency, voltage, active and reactive power for the 80 kW loading condition

4.1.3 Case 3: Reactive Power Mismatch

This case highlights the effect of the proposed method on the reactive power mismatch between the load and the DG. The figures below show the frequency, voltage, and the active and reactive power during islanding, without the proposed method and with the proposed method, for loads with frequency threshold rating 60.5 Hz, 60.25Hz, 59.5Hz and 59.3Hz.

- <u>*Condition 1: P = 100 kW, f = 60.5 Hz*</u>

In this condition the reactive power varies with the frequency threshold and is equal to 60.5 Hz while the active power fixed constant is 100kW. As shown in Figure 26, the frequency will deviate above the threshold frequency at the moment of islanding, and then the p-*f* droop detects the transition and change the frequency back to the resonant frequency. In addition, the voltage, and the active and reactive power returns back to the values before islanding.

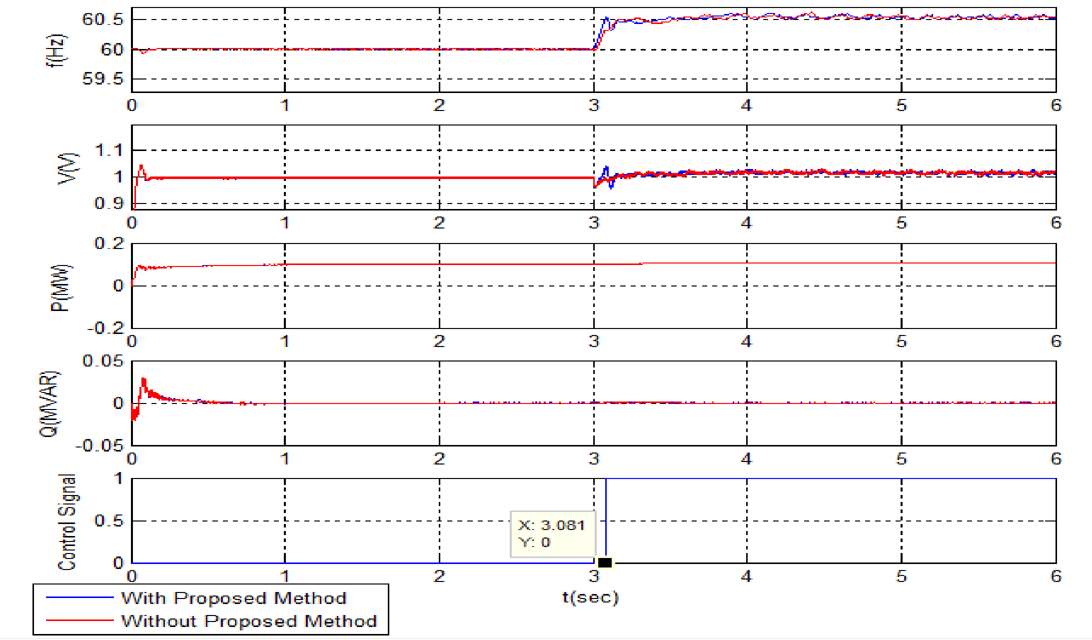

Figure 26: Frequency, voltage, active and reactive power for the 60.5 Hz loading condition

- *Condition 2: P = 100 kW, f = 60.25 Hz*

Based on the IEEE 1547 standard, the reactive power mismatch was tested at f = 60.25 Hz. Figure 27 , illustrates that when the islanding occurs the frequency deviates outside the threshold limit that causes the system to become unstable. As a result, the other parameters also become unstable. With the proposed method, the islanding can be detected when the frequency is higher than 60.5Hz, then it returns to 60.25Hz.

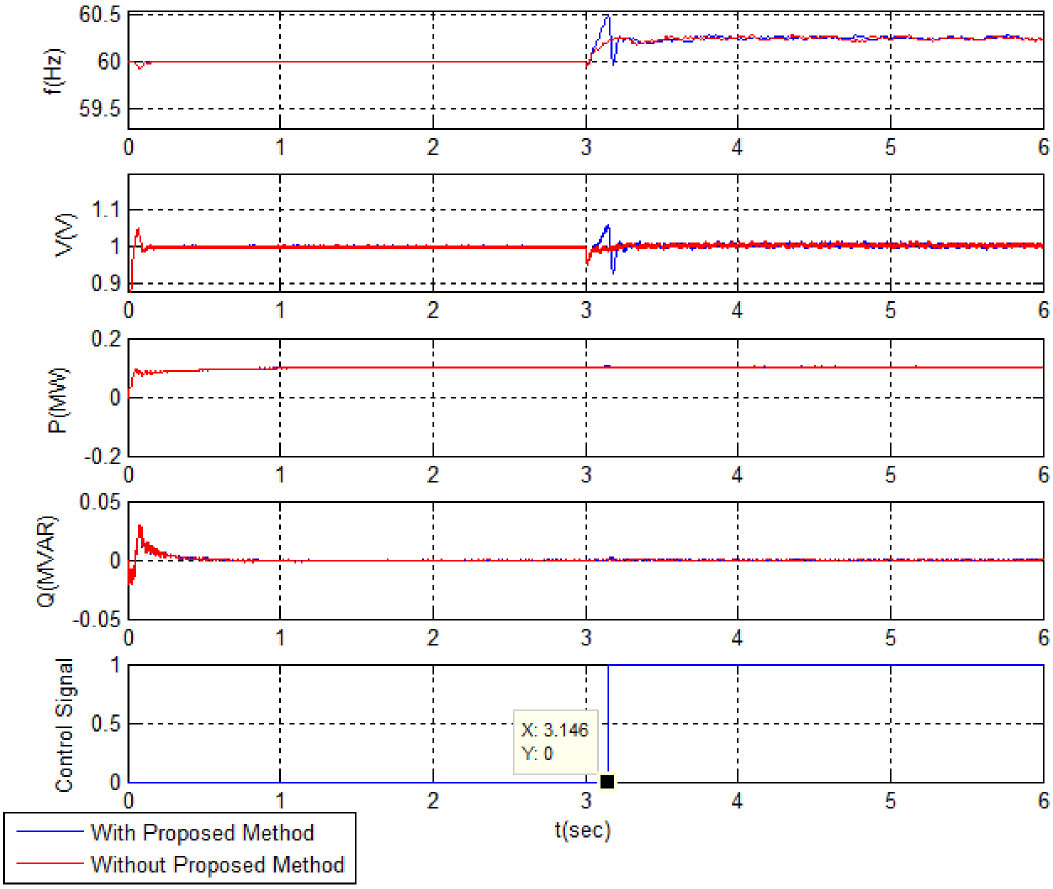

Figure 27: Frequency, voltage, active and reactive power for the 60.25 Hz loading condition

- <u>*Condition 3: P = 100 kW, f = 59.5 Hz*</u>

The system was tested when the reactive power mismatch for the frequency rating of f = 59.5 Hz. The frequency and voltage deviate outside the threshold limit at the moment of the islanding, thus the proposed algorithm is capable of detecting islanding and stabilizing the system parameters as shown in Figure 28.

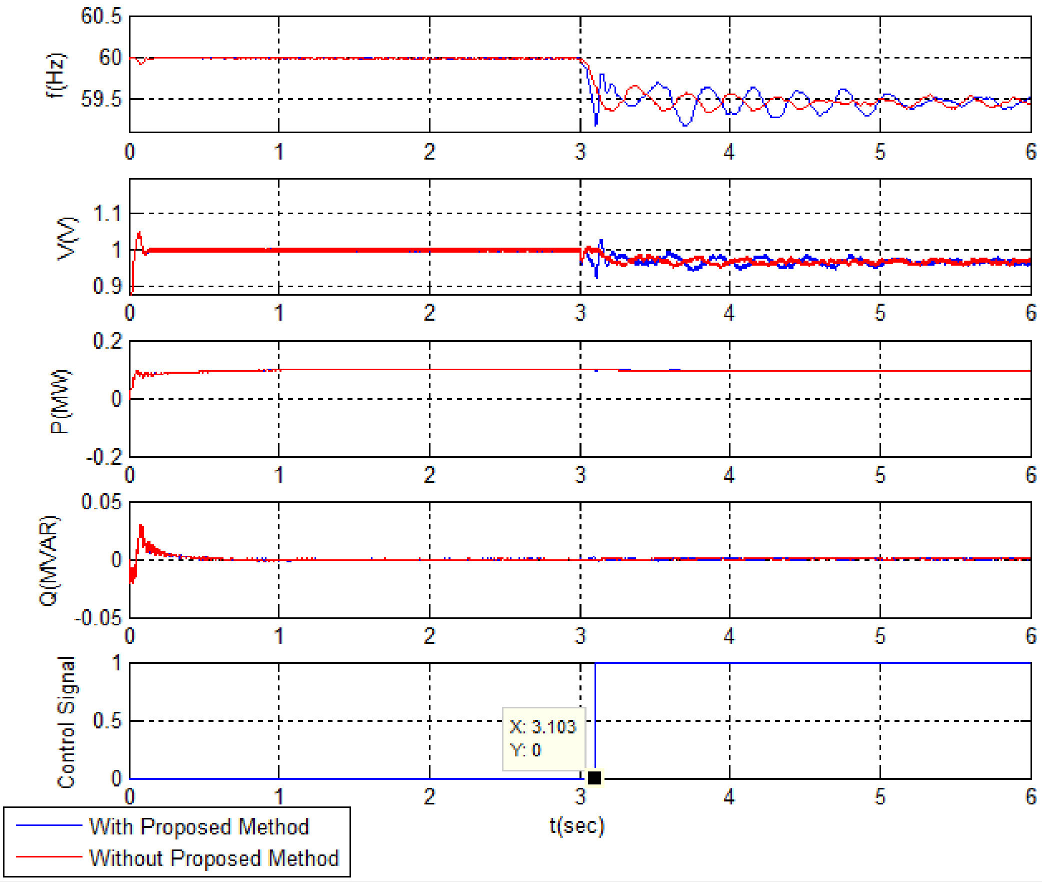

Figure 28: Frequency, voltage, active and reactive power for the 59.5 Hz loading condition

- <u>*Condition 4: P = 100 kW, f = 59.3 Hz*</u>

In this condition, the load is adjusted to operate at the reactive power mismatch with f = 59.3 Hz. The amount of the reactive power mismatch causes the frequency violates the limits during the islanding event. Figure 29, shows the effect of using the proposed method. The proposed method stabilizes all the system parameters after the islanding event, but without the proposed method the system becomes unstable.

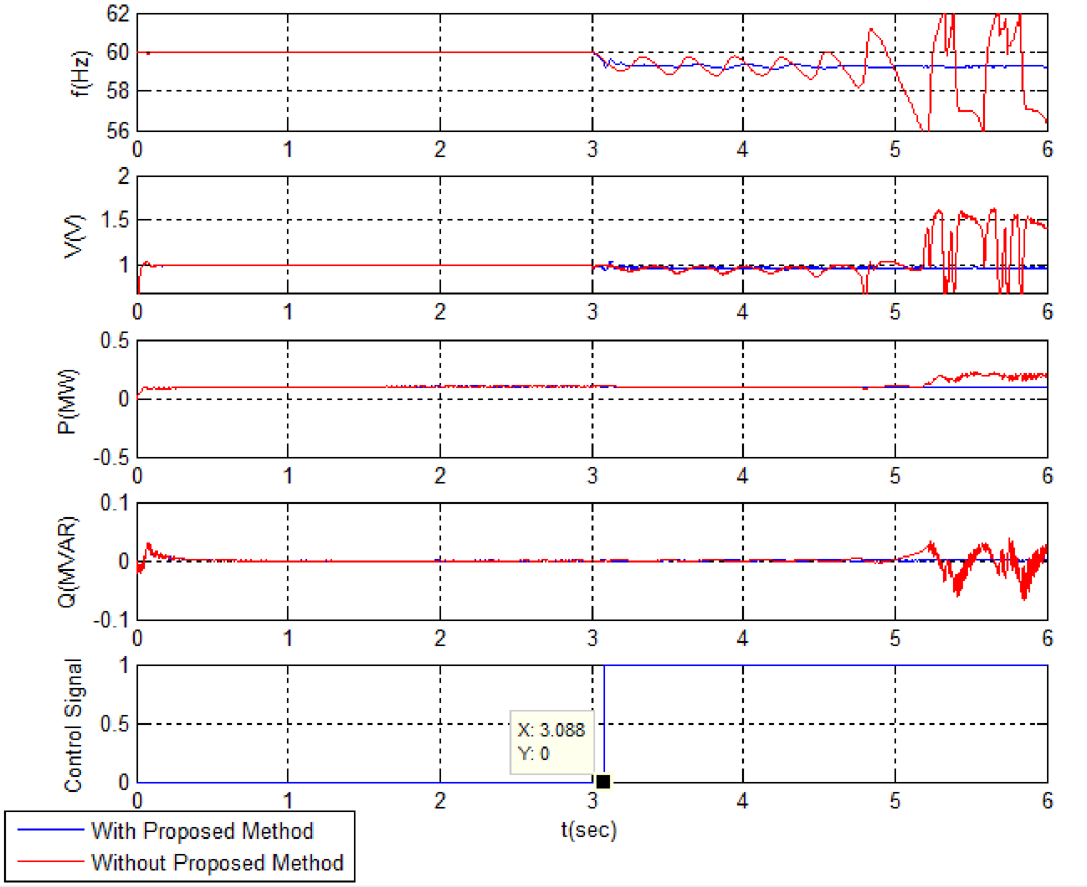

Figure 29: Frequency, voltage, active and reactive power for the 59.3 Hz loading condition

4.1.4 Summary of Simulation Result of Single DG

Tables 8 and 9 illustrate the detection response time variables in accordance to the active and reactive power mismatch following the proposed method once islanding occurs.

- *Case 1: Zero Active and Reactive Power Mismatch*

Zero active and reactive power mismatch takes 513ms to detect the transition, which is the slowest time response comparing with the other cases.

- *Case 2: Active Power Mismatch*

Table 8 shows that the lowest detection time occurs when the active power mismatch +20% is between the load and the DG. The active power mismatch takes a long time to detect islanding compared with other cases.

- *Case 3: Reactive Power Mismatch*

The reactive power mismatch is fast in detecting the islanding event in less than 150ms as shown in Table 9.

Table 8: Performance of proposed method with variation in load active power

Power (kW)	Detection Time(s)
80	3.023
90	3.242
100	3.513
110	3.348
120	3.019

Table 9: Performance of proposed method with variation in load resonance frequency

Frequency	Detection Time (s)
59.3	3.088
59.5	3.103
60	3.513
60.25	3.146
60.5	3.081

4.2 Multiple DG Simulation Results

It was necessary to test the proposed method performance using other options. Multiple identical DGs were tested under different loading conditions. These are illustrated in the below figures.

4.2.1 Case 1: Zero Active and Reactive Power Mismatch

Based on the IEEE 1547 standard, zero active and reactive power were tested (P = 200 kW, f = 60 Hz**)** in order to ensure the feasibility of the proposed method in the worst case. Figure 30, shows the voltage deviation beyond the threshold value when islanding occurs at t = 5s. With the proposed method the transition is detected at t = 5.517 s, and the parameters return back to the initial stabilized state within the common threshold value.

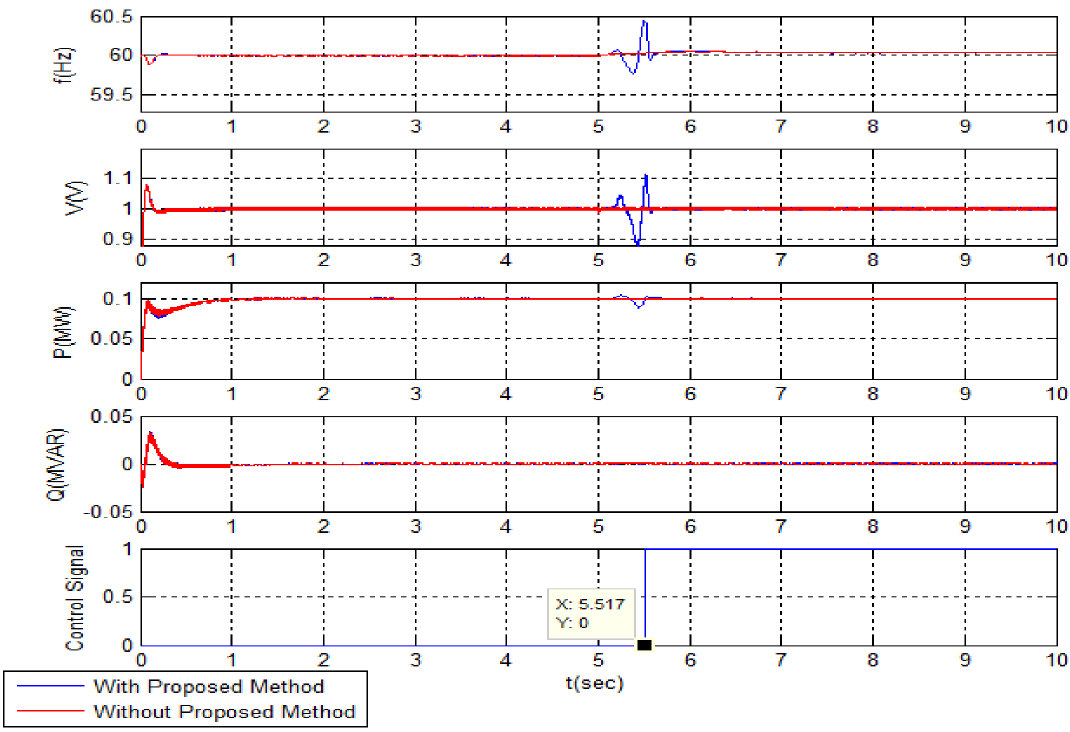

Figure 30: Frequency, voltage, active and reactive power for the 200 kW loading condition

4.2.2 Case 2: Active Power Mismatch

To test the performance of the proposed method during the islanded mode, the active power of the load was adjusted to operate the inverter at ±10% and ±20 of its rated active power output.

Figures 31 and 32, present the result of Conditions 1 and 2, when the active power of the load is adjusted to place the inverter at ±10% of the rated output power parameters, which are P=210 kW and P=190 kW respectively. The moment the DGs are isolated from the grid at t = 5s, the DGs lose their stability, and the frequency drops below the threshold limit to be less than 59.3Hz for both conditions. The proposed method is able to detect the islanding in less than 500ms and stabilize the system parameters.

- *Condition 1: P = 210 kW, f = 60 Hz*

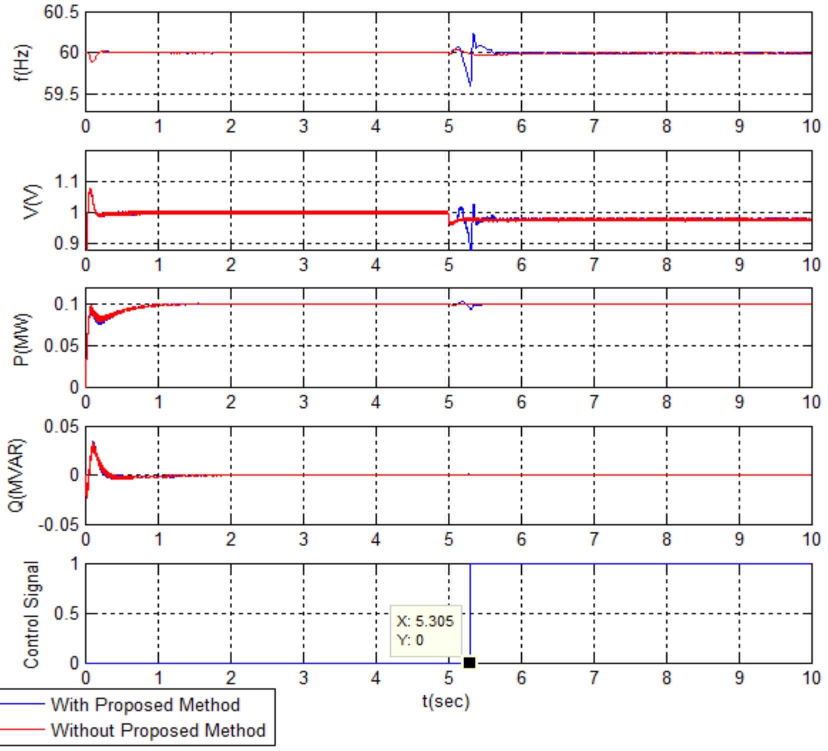

Figure 31: Frequency, voltage, active and reactive power for the 210 kW loading condition

- *Condition 2 : P = 190 kW, f = 60 Hz*

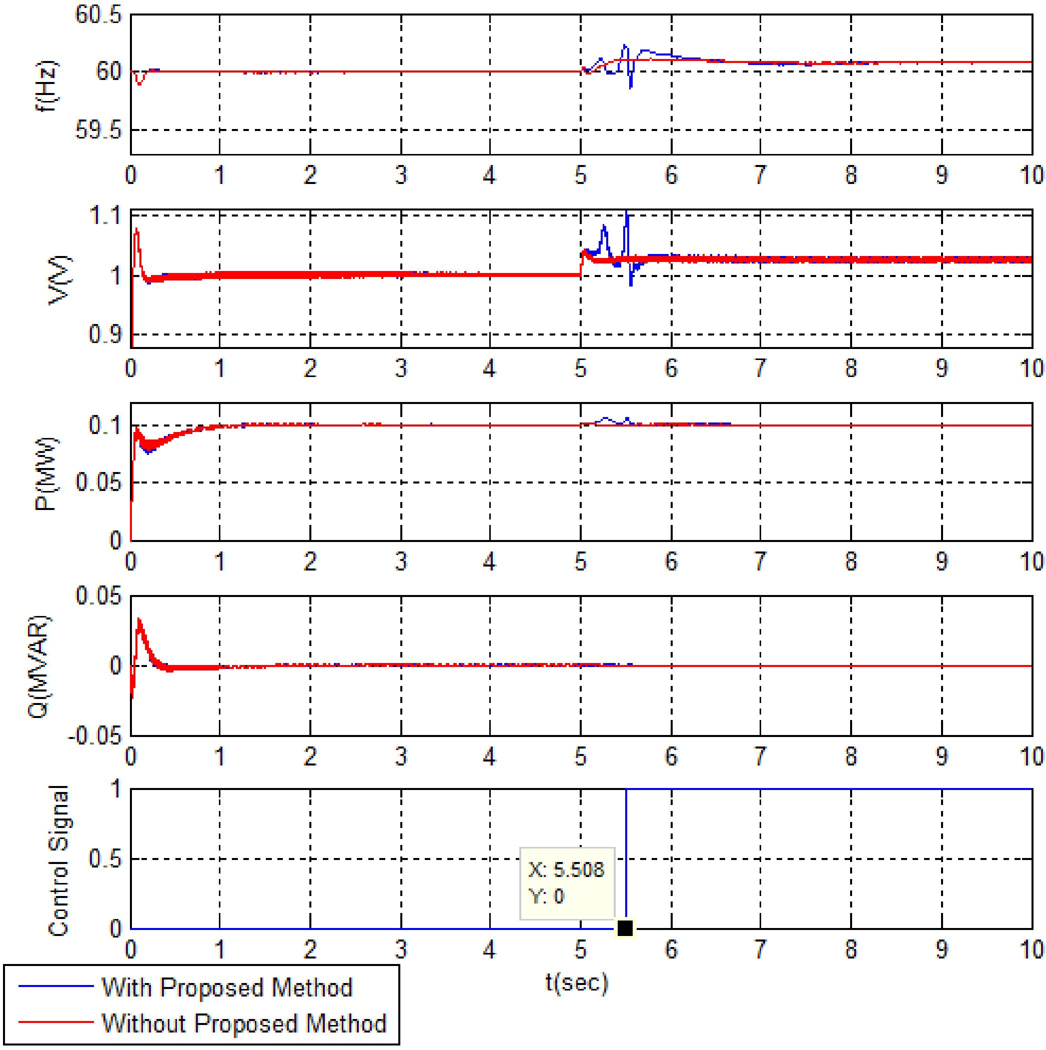

Figure 32: Frequency, voltage, active and reactive power for the 190 kW loading condition

Figures 33 and 34 highlight the simulation results of Conditions 3and4 when the active power load mismatches the active power of the DGs by ±20%. Both conditions show that when the islanding occurs, the frequency and voltage violate the threshold rating values and the other system parameters become unbalanced. The proposed method stabilizes the system parameters when islanding is detected.

- *Condition 3 :P = 220 kW, f = 60 Hz*

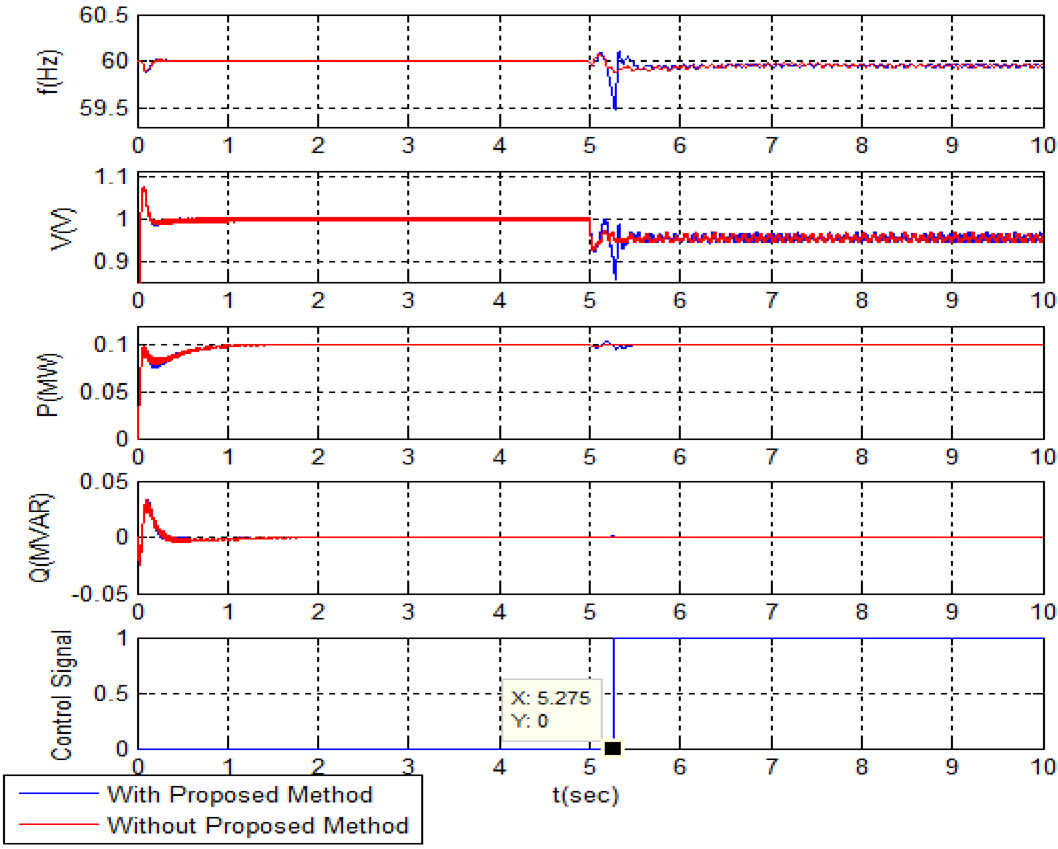

Figure 33: Frequency, voltage, active and reactive power for the 220 kW loading condition

- *Condition 4 :P = 180 kW, f = 60 Hz*

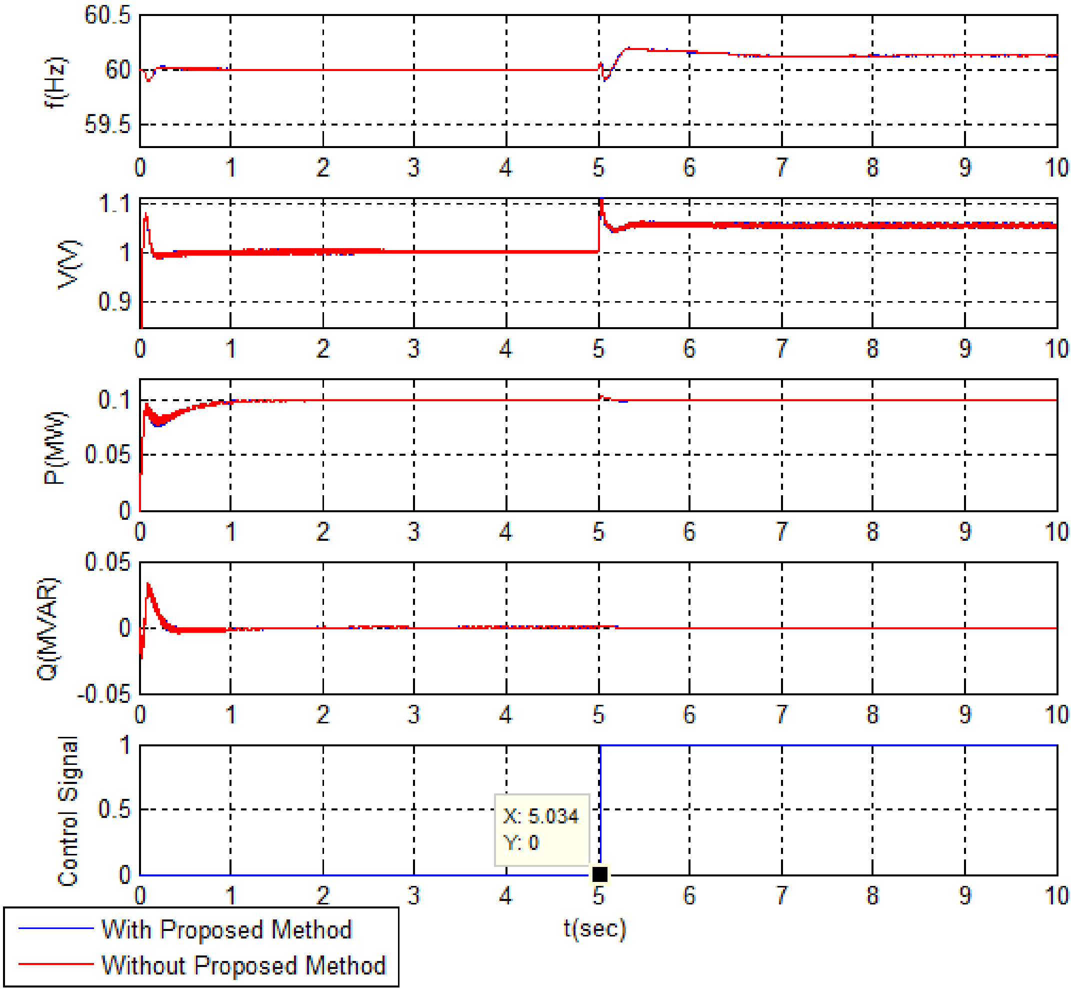

Figure 34: Frequency, voltage, active and reactive power for the 180 kW loading condition

4.2.3 Case 3: Reactive Power Mismatch

The proposed method is tested for islanding conditions including RLC load with reactive power mismatch, for loads with frequency threshold ratings of 60.5 Hz, 60.25Hz, 59.5Hz and 59.3Hz.

- *Condition 1: P = 200 kW, f = 60.5 Hz*

Figure 35, shows the stabilized condition with no islanding detection technique, in which the frequency drifts upward to its threshold limits when islanding takes place. When the islanding is detected with the proposed method, the frequency drifts towards its resonance value, and the system returns to a stable status.

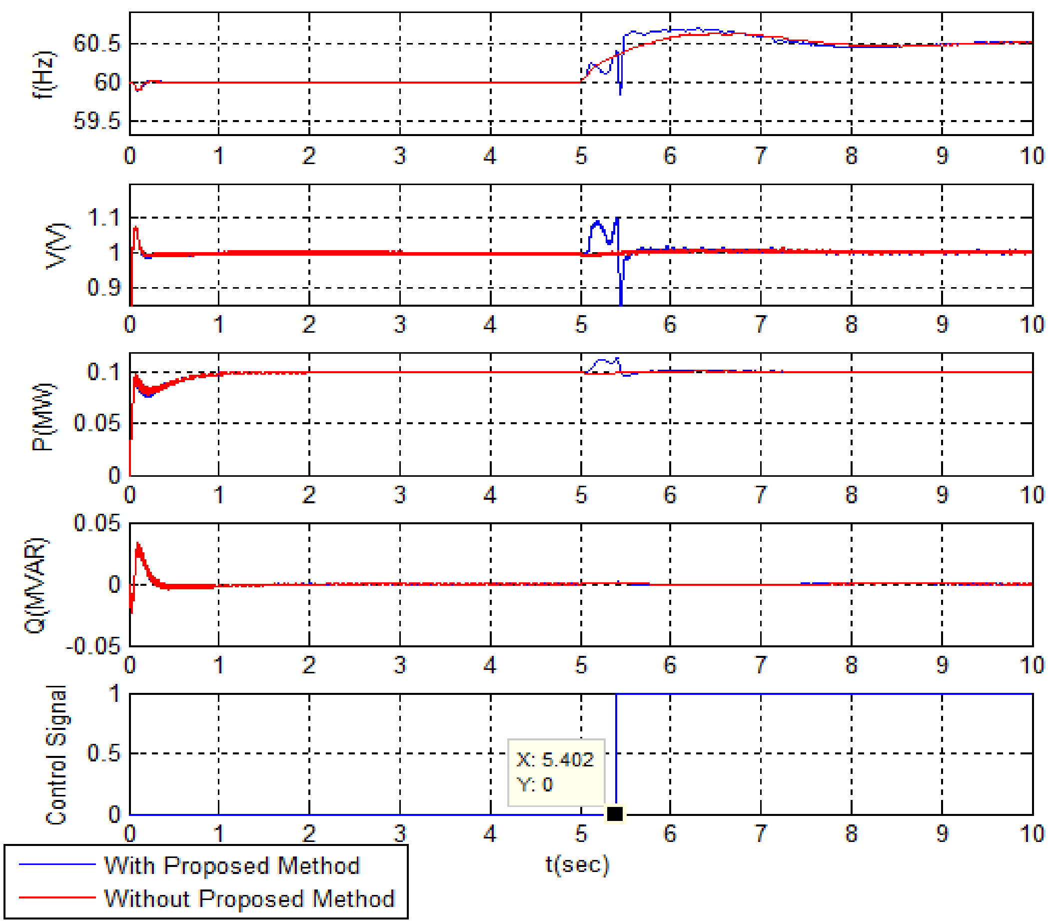

Figure 35: Frequency, voltage, active and reactive power for the 60.5 Hz loading condition

The reactive power mismatch is tested at f = 60.25 Hz based on the IEEE 1547 standard. Figure 36, demonstrates that when the islanding happens, the frequency, voltage, and active power deviate outside the threshold limit whereas the reactive power remains unchanged. While with the proposed method, the islanding is detected at t = 5.397s and the frequency drifts toward the resonance value of 60.25 Hz.

- *Condition 2: P = 200 kW, f = 60.25 Hz*

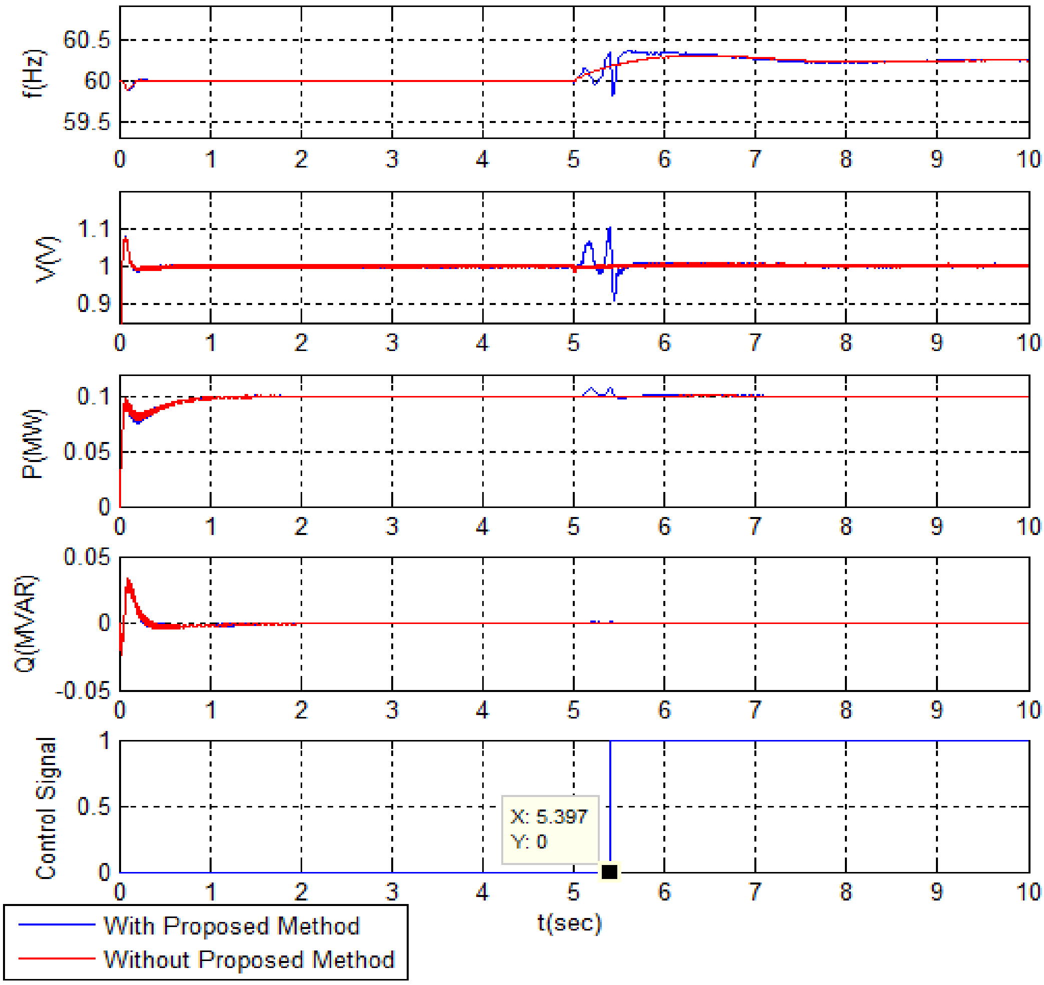

Figure 36: Frequency, voltage, active and reactive power for the 60.25 Hz loading condition

During reactive power mismatch, when the frequency rating at f = 59.5 Hz, islanding takes place causing deviation outside the threshold limits in frequency and voltage, so that the system loses its stability. With the proposed method the frequency is forced to drift toward its resonant frequency, and the system becomes balanced as shown in Figure 37.

- *Condition 3: P = 200 kW, f = 59.5 Hz*

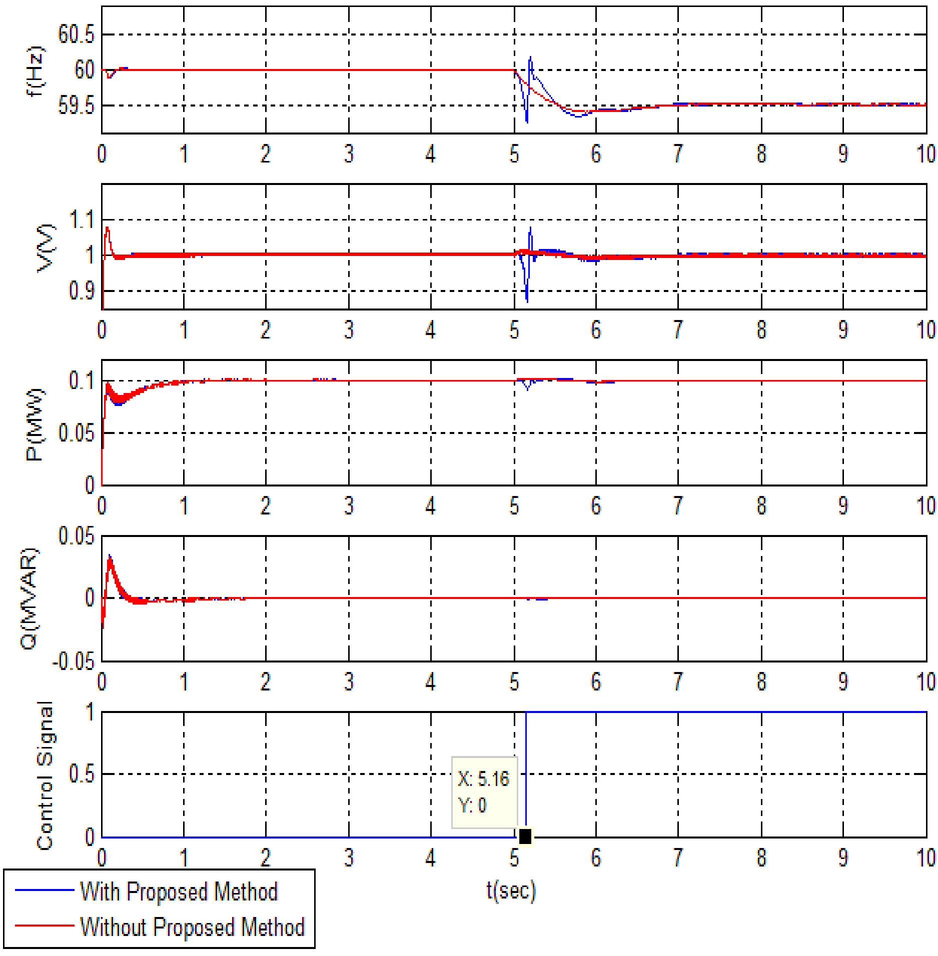

Figure 37: Frequency, voltage, active and reactive power for the 59.5 Hz loading condition

The proposed method is again applied in another condition, when the reactive power mismatch with the frequency f = 59.3 Hz. Figure 38, shows that when islanding occurs, the frequency deviates away from the threshold limits and the system loses its stability. The proposed method detects the islanding and stabilizes the system.

- *Condition 4: P = 200 kW, f = 59.3 Hz*

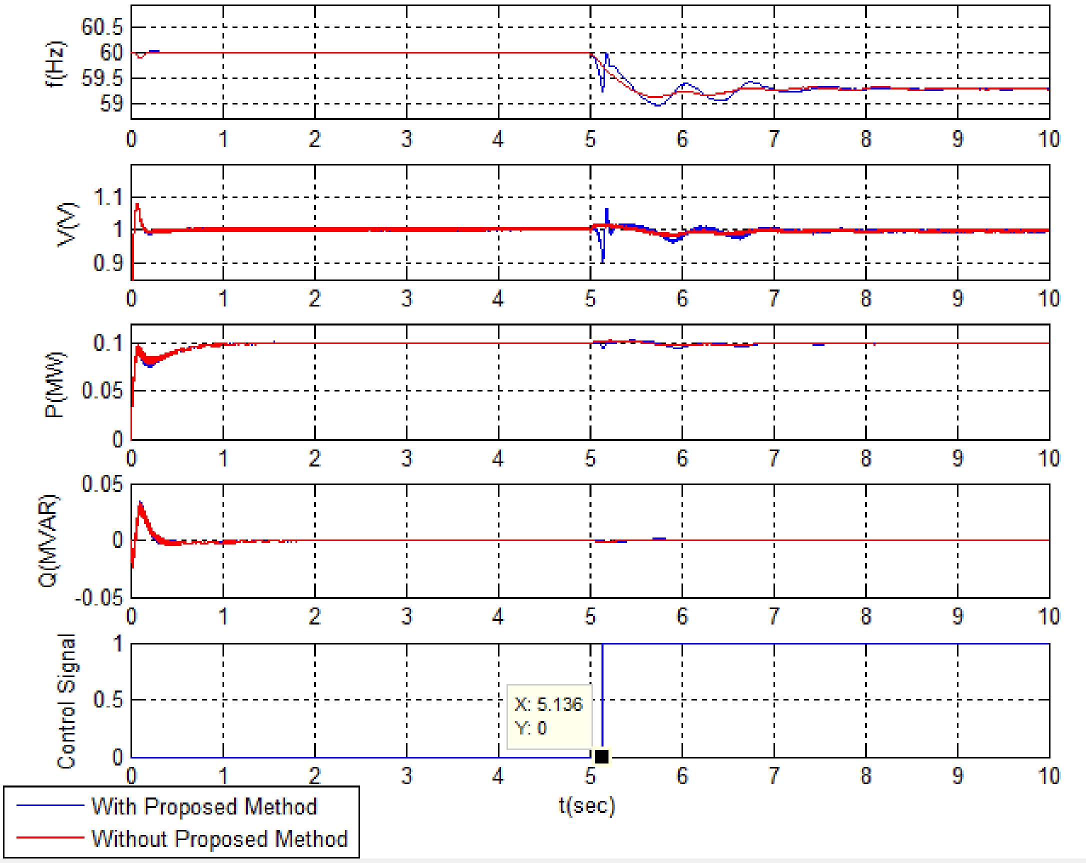

Figure 38: Frequency, voltage, active and reactive power for the 59.3 Hz loading condition

4.2.4 Summary of Simulation Result of Multiple DGs

Tables 10 and 11 show the detection response time variables in line with the active and reactive power mismatch following the proposed method once islanding happens.

- *Case 1: zero active and reactive power mismatch*

In this case, the most prominent aspect is that zero active and reactive mismatches were able to detect islanding in a slowest time that time being less than 600 ms compared to active and reactive power mismatch.

- *Case 2: active power mismatch*

The active power mismatch takes a long time to detect islanding compared with reactive power mismatch. The shortest detection time occurs when the active power mismatch is equal to 180 kW leveling 5.034 ms as shown in Table 10.

- *Case 3: reactive power mismatch*

The fastest detection case is the reactive power mismatch as it can detect islanding in less than < 400 ms as shown in Table 11.

Table 10: Performance of proposed method for multiple DGs with variation in load active power

Power (kW)	Detection Time (s)
180	5.034
190	5.508
200	5.517
210	5.305
220	5.275

Table 11: Performance of proposed method for multiple DGs with variation in load resonance frequency

Frequency	**Detection Time(s)**
59.3	5.136
59.5	5.16
60	5.517
60.25	5.397
60.5	5.402

Chapter 5: Conclusion and Future Work

5.1 Conclusion

This thesis introduces an islanding detection method for micro-grids based on droop control. Basically this method relies on modifying the droop coefficient, which alternatively changes and modifies the system from stable to unstable situations symbolizing that islanding is taking place. At that time, the droop automatically deals with the change and responds to stabilize the system. This is a key feature and a success indicator since the droop has the ability to cope with any expected or unexpected changes and repair them. Appling the proposed droop control method shows reliability and efficiency especially since it has been proven by testing its effectiveness in two models, which are single DG and multiple DGs, to ensure better performance. This research investigates different islanding techniques and lists various methods. Later, it compares and evaluates their reliability and effectiveness. Adding to that, the research proposes and suggests a new islanding detection method for micro-grids using P-*f* droop control. Therefore, it determines and evaluates the different features of the proposed method, so that it can be easily implemented in micro-grid networks. For instance, the proposed method seems to be as reliable as it is accurate since it operates in different conditions, on top of its ability to stabilize the system once islanding occurs.

5.2 Contribution

The thesis is expected to tackle a timely topic that is of relevance to the UAE. The UAE has set goals to increase the penetration of renewable energy in the power system, knowing that the proposed method integrates that through the micro-grid penetration, which is viewed as a worldwide energy saving solution, into the power system. The main contribution of this thesis introduces and proposes the concept of micro-grid islanding detection for micro-grids equipped with inverter based DG using P-f droop control where the status of the micro-grid is detected based on adaptively modifying the droop slope. The droop coefficient is chosen such that the micro-grid is stable while grid is connected, but stays unstable as soon as an islanded micro-grid operation is initiated. The droop coefficient is adaptively modified, once the micro-grid shifts from grid connected to islanded operation, to stabilize the micro-grid for the islanded mode of operation. The proposed method has been tested considering various active and reactive power mismatch conditions, to ensure better performance. The results show that the proposed approach is capable of detecting a transition of the state of the micro-grid within less than 600 ms and is capable of stabilizing the system once the islanded operation is detected. This work provides an approach that would help utility operators in determining the existence of any islanded micro-grids within its system.

5.3 Scope of Future Work

The thesis proposed an islanding detection method for micro-grids equipped with an inverter based DG. The work can be further extended to include micro-grids with other types of DGs such as induction based or synchronous based DGs. Furthermore, the focus of the thesis on one type of droop control, namely, the P-*f* /Q-V droop. In literature, various types of droop controls have been proposed for operating micro-grids. Another possible extension would be to investigate the applicability of the proposed approach on micro-grids with other types of droop controls and possibly propose new islanding detection schemes. A future direction can include the development of a prototype of the micro-grids with the proposed detection scheme for laboratory testing.

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