ISLANDED OPERATION OF PHOTOVOLTAIC SYSYTEMS WITH THE USE OF BI-DIRECTIONAL INVERTERS

By

YONG WUI KIAN

A dissertation submitted to the Department of Electrical and Electronics Engineering,
Lee Kong Chian Faculty of Engineering and Science,
Universiti Tunku Abdul Rahman,
in partial fulfilment of the requirements for the degree of
Master in Engineering Science
September 2015

ABSTRACT

ISLANDED OPERATION OF PHOTOVOLTAIC SYSTEMS WITH THE USE OF BI-DIRECTIONAL INVERTERS

Yong Wui Kian

Sustainable energy generated from renewable resources such as sunlight, wind and water has become the favourable choice due to its environmental friendly and carbon emission free characteristics. Thus, the Malaysian government has introduced a series of new incentives, including feed-in tariff and tax reduction to promote the utilisation of renewable energy sources. The Photovoltaic (PV) systems is a promising renewable energy source in Malaysia as this region is blessed with abundant solar energy. With the high penetration of PV systems in the distribution networks, islanded operation of PV systems is likely to happen. However, islanded operation with renewable energy sources is not allowed under existing regulatory framework due to safety considerations.

This dissertation proposes the integration of bi-directional inverters into distribution networks for allowing the islanded operation of photovoltaic systems. The main objective is to ensure the continuity of power supply especially in those areas where the occurrence of power interruption is high. The islanded network can remain energised by the renewable energy sources while the network voltage and frequency are well-maintained by the energy storage system. Thus, the reliability of the distribution network can be greatly improved.

Several experimental studies have been carried out to validate the feasibility of conducting the islanded operation of PV systems with the use of bi-directional inverter. The operational boundary of the droop controlled bi-directional inverter has been derived to indicate the ability of the bi-directional inverter to maintain the voltage and frequency within the statutory limits. A control algorithm is developed to adjust the battery charging current of the bi-directional inverter, so that the voltage and frequency of the islanded network can still be maintained within the statutory limits even though the power mismatches are huge.

The experimental results demonstrate the effectiveness of the developed control algorithm in the bi-directional inverter to allow the islanded operation of PV systems. The work proposed in this dissertation could be beneficial to the utility company which is always striving to improve the reliability of power supply continuity while maintaining the desired growth of renewable energy in the Malaysian distribution networks.

ACKNOWLEDGEMENTS

The author would like to extend his sincere thanks to the supervisor, Prof. Ir. Dr. Lim Yun Seng, and co-supervisor, Dr. Stella Morris, for their excellent supervision, support and encouragement throughout the research and preparation of this thesis. Also, the author would like to thank of his many colleagues, in particular Ms. Wong Jianhui, Mr. Tang Jun Huat and Mr. Chua Kien Huat for their assistance and invaluable advice. He also extends his special thanks to his beloved family for their endless support and encouragement.

Last but not least, the author is thankful for the financial support sponsored in part by the Ministry of Energy, Green Technology and Water through the scheme of AAIBE (Akaun Amanah Industri Bekalan Elektrik).

APPROVAL SHEET

This dissertation entitled **"ISLANDED OPERATION OF PHOTOVOLTAIC SYSTEMS WITH THE USE OF BI-DIRECTIONAL INVERTERS"** was prepared by YONG WUI KIAN and submitted as partial fulfilment of the requirements for the degree of Master in Engineering Science at Universiti Tunku Abdul Rahman.

Approved by:

____
(Prof. Ir. Dr. Lim Yun Seng)
Date:
Supervisor
Department of Electrical and Electronics Engineering
Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

____
(Dr. Stella Morris)
Date:
Co-supervisor
Department of Electrical and Electronics Engineering
Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

LEE KONG CHIAN FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date:

SUBMISSION OF DISSERTATION

It is hereby certified that **YONG WUI KIAN** (ID No: **13 UEM 02529**) has completed this thesis entitled "**ISLANDED OPERATION OF PHOTOVOLTAIC SYSTEMS WITH THE USE OF BI-DIRECTIONAL INVERTERS**" under the supervision of Prof. Ir. Dr. Lim Yun Seng (Supervisor) from the Department of Electrical and Electronics Engineering, Faculty of Engineering and Science, and Dr. Stella Morris (Co-Supervisor) from the Department of Electrical and Electronics Engineering, Faculty of Engineering and Science.

I understand that the University will upload the softcopy of my thesis in pdf format into UTAR Institutional Repository, which may be made accessible to the UTAR community and public.

Yours truly,

____

(YONG WUI KIAN)

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

____

(YONG WUI KIAN)

Date ____________________

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ ABBREVIATIONS

AC	Alternating current
AGM	Absorbent Gel Material
CO_2	Carbon dioxide
DC	Direct current
DG	Distributed generation
FiT	Feed-in-Tariff
FSPC	Frequency shift power control
GBI	Green building index
HAWT	Horizontal-axis wind turbine
IEC	International electro-technical commission
IEEE	Institute of electrical and electronic engineers
LV	Low voltage
MPPT	Maximum power point tracking
NDZ	Non detection zone
OUF	Over-under frequency
OUV	Over-under voltage
PCC	Point of common coupling
PSH	Peak sun hours
PV	Photovoltaic
RE	Renewable energy
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index

SEDA	Sustainable energy development authority
SOC	State of charge
SESB	Sabah electricity sdn. bhd.
SESCO	Sarawak electricity supply corporation
TNB	Tenaga nasional berhad
UNFCCC	United nations framework convention on climate change
US	United states of america
VAWT	Vertical-axis wind turbine
VSD	Variable speed drive

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Research Background

Greenhouse gases emission and hence global warming produced by fossil fuel combustion has raised the awareness of the public. Rising fossil fuel prices and significant environmental issues have driven the growth of renewable energy sources over the past decades. Renewable energy generated from clean and inexhaustible sources such as sunlight, wind and water is recognised as an alternative solution to reduce the dependency on non-depleting sources and improve the environmental quality for a better living. In perceiving the importance of energy sustainability, the Malaysian government has introduced a series of new incentives such as feed-in tariff and tax reduction for green technologies, to promote the use of renewable energy under Renewable Energy Act 2011.

Photovoltaic (PV) power generation provides a great potential among the renewable energy sources available in Malaysia. One of the reasons is that Malaysia as one of the countries located in the equatorial region, is blessed with substantial sunlight. According to the Malaysian Meteorological department, Malaysia receives an average of 6 hours sunshine daily. Figure 1.1 shows that

Malaysia receives averaging 4 to 6 hours of peak sunlight per day. Hence, it is anticipated that the PV systems installation in Malaysia will increase substantially in the future. At present, the conventional electrical network is organised and operated in unidirectional power flow whereas the integration of the renewable energy that injects power to the utility grid has substantially changed into bi-directional power flow.

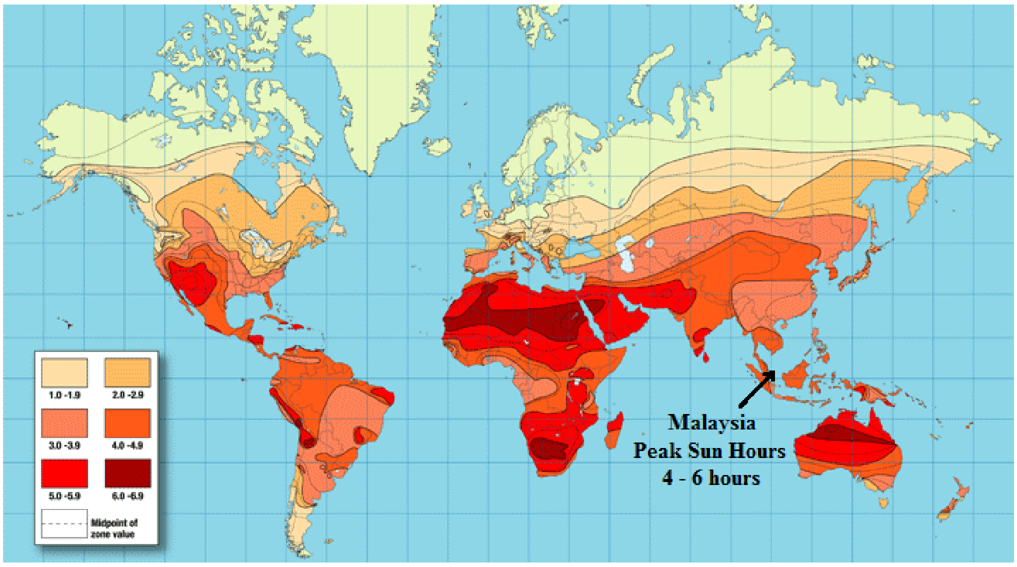


Figure 1.1: Global daily amount of solar energy in hours **(**Source: http://www.altestore.com/howto/Solar-Electric-Power/Reference-Materials/Solar-Insolation-Map-World/a43/**)**

The utility company pays substantial attention to the reliability of power supply. However, improving the reliability of power supply in the remote area is hard to be realised because of the interconnection between the mains and remote networks is always subjected to various faults. As a result, the interconnection is very often out of service, leading to high occurrence of power interruptions to the customers.

The Malaysian government is striving to increase the penetration of PV on the distribution network. The cumulative annual PV power generation capacity for the year 2013 to 2014 has increased by 52 GWh (SEDA, 2014c). Under the existing regulatory framework, all the PV generations are required to shut down when the grid is out of service. However, customers cannot utilise the available renewable energy generated when the PV is shut down. This practice is not only to protect the customer's equipment, but also for the safety of the working personnel on the distribution networks. In order to increase the benefits of exploiting solar energy, it is important to allow the PV system to remain operating even though when the grid is out of service. Hence, islanded operation with PV systems is needed particularly in remote areas in Malaysia, where power interruption is very common.

A mechanism of regulating the voltage and frequency of the islanded network within the acceptance limit is needed throughout the islanded operation with PV systems. At present, rotary based machine such as synchronous generator and diesel generator can be utilised to regulate the voltage and frequency of the islanded network (Best et al., 2007). However, fossil fuel power plants during the islanded operation appear to be a non-environmental friendly selection due to greenhouse gases emission (Jakhrani et al., 2012). In addition, the transportation cost of the fossil fuels to the isolated areas for power generation is high.

Apart from this method, the energy storage system with proper control is able to maintain the voltage and frequency of the islanded network. This method can ensure an uninterruptible power supply of the islanded network. Several research studies have been proposed on the controller which can regulate voltage and frequency during islanded operation (Balaguer et al., 2011; Kamel, et al., 2011; Soo et al., 2013). However, there is not much relevant study on energy storage system that is designed to cope with the islanded operation with renewable energy. In addition, most of the previous work was done on simulation studies without experimental validation. Therefore, a further experimental study is necessary.

Due to the limitation encountered by using diesel generator and energy storage system during the islanded operation, a bi-directional inverter with energy storage system is proposed in this research work. The bi-directional inverter with droop characteristics can control the power output based on the frequency and voltage of the islanded network. An experimental work has been carried out to investigate the impact of islanded operation of PV systems to the Malaysian distribution network. From this study, this dissertation demonstrates that the islanded operation of PV systems is a viable option to improve the reliability of the Malaysian distribution network.

1.2 Objectives

The main objectives of this research are listed as follows-

i. To develop an experimental setup of a low-voltage distribution network with renewable energy sources to study the islanded operation of the PV systems.
ii. To investigate the voltage and frequency changes of the isolated network during the islanded operation of the PV systems.
iii. To evaluate the feasibility of a bi-directional inverter with batteries integrated on the distribution network for conducting islanded operation of the PV systems.
iv. To develop and create a suitable control algorithm with the bi-directional inverter to maintain the voltage and frequency of the islanded network even though the power mismatches is large during the islanded operation of the PV systems.

1.3 Research Methodology

This research focuses on an experimental approach to investigate the feasibility of allowing the islanded operation of the PV systems to be integrated into the Malaysian distribution networks. The research objectives are to be achieved by accomplishing the following steps.

Step 1: Literature review

A detailed study is to be conducted on the potential and development of the renewable energy in Malaysia. This methodology outlines the regulatory framework introduced by the Malaysian government to promote the installation of green technology on the existing distribution networks. A detailed study is to be carried out on the existing solution to allow for an islanded operation.

Step 2: Experimental design

A case study of the Malaysian low-voltage distribution network is to be conducted. An experimental setup of a low-voltage distribution network consisting of network emulator, PV systems and load bank is to be designed and constructed at the university laboratory for testing and verification studies.

Step 3: Operating mechanism of the bi-directional inverter

This methodology provides an in-depth study on the operating principle of the bi-directional inverter. The sophisticated bi-directional inverter is featured with several unique controls such as droop characteristics, battery management system and frequency shift power control which provide an adequate control on the islanded network throughout the islanded operation of PV systems.

Step 4: Preliminary study on the islanded operation with PV systems

The feasibility of islanded operation of PV systems is to be investigated and examined in the low-voltage distribution network at the laboratory with this methodology.

Step 5: Integration of the bi-directional inverter

This step focuses on the integration of the bi-directional inverter with batteries into the experimental network for conducting the islanded operation of PV system. The performance analysis of the bi-directional inverter is to be conducted from numerous case studies in order to evaluate the performance of the bi-directional inverter during the islanded operation with the PV systems.

Step 6: Implementation with proposed control algorithm

A control algorithm is to be developed to enhance the performance of the bi-directional inverter during the islanded operation of PV systems. The real power flow of the bi-directional inverter is to be manipulated through the control algorithm during the islanded operation of PV systems while maintaining the voltage and frequency of the islanded network within an acceptable level.

Step 7: Performance evaluation

Several case studies are to be carried out with various load conditions in order to validate the effectiveness of the developed control algorithm on the bi-directional inverter in order to allow the islanded operation with the PV systems.

1.4 Scope of Dissertation

The rest of this dissertation is organised as follows.

Chapter 2 gives a general overview of the characteristics and development of the renewable energy sources in Malaysia, various incentives introduced by the Malaysian government and the international standards with renewable energy sources. A literature study on various technical aspects and potential development on the islanded operation of PV systems is also discussed here. Furthermore, several types of islanding detection methods are illustrated in this chapter.

Chapter 3 presents a detailed experimental setup of the low-voltage distribution network with renewable energy sources. The details of the design on each component are discussed here.

Chapter 4 demonstrates the detailed operating mechanisms of the proposed bi-directional inverter integrated with batteries. Several unique control schemes in the bi-directional inverter which provide voltage and frequency regulation are demonstrated.

Chapter 5 illustrates the experimental validation of the proposed approach with various load conditions during the islanded operation of PV systems. The experimental results on voltage and frequency changes of the islanded network are presented. An operational boundary of the bi-directional inverter is defined to evaluate the performance of the bi-directional inverter during the islanded operation of PV systems. Several case studies with different scenario are presented to test the effectiveness of the developed control algorithm for conducting the islanded operation of PV systems while keeping the voltage and frequency of the islanded network within the statutory limits.

Finally, Chapter 6 summarises the key findings of the research. In this chapter, the conclusion of the research and a discussion of the potential future work are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Renewable energy sources have emerged to become one of the solutions to reduce the dependency on fossil fuels. At present, the electricity generation in Malaysia is quite similar to that of some other countries that are highly dependent on fossil fuels. Figure 2.1 shows the electricity generation from various sources in Malaysia. In 2012, Malaysia recorded a total electricity generation of 134,477 GWh. As for the year 2012, natural gas and coal contribute more than 85 % of the power generation sector in Malaysia (Energy Commission, 2014a). Due to the limited amount of natural gas and coal, Malaysia is required to import fossil fuel from its neighbouring countries such as Indonesia and Thailand to cope with the increased demand (US Department of Energy Information Administration, 2013). Therefore, the Malaysian government has introduced a series of renewable energy incentives to promote the usage of renewable energies and hence to scale down the reliance on fossil fuels (Wong, 2011). The Malaysian government expects that the amount of renewable energy generation will increase from 5.5% of the total power generation in year 2010 to 11.0 % in the year 2020 (KeTTHA, 2009).

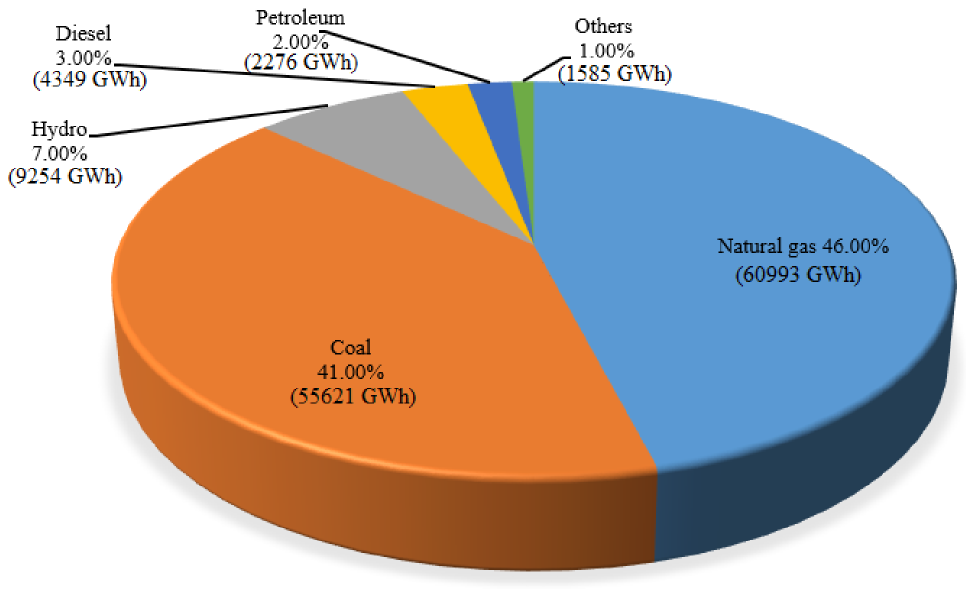


Figure 2.1 Electricity generation at Malaysia in year 2012

2.2 Utility Companies in Malaysia

The Malaysian electricity sector is mainly supplied by three major utility companies. The main electricity utility company, Tenaga Nasional Berhad (TNB) is the sole power provider in peninsular Malaysia whereas the Sabah Electricity Sdn. Bhd. (SESB) and Sarawak Electricity Supply Corporation (SESCO) are the main utility companies in East Malaysia. Figure 2.2 depicts the distribution of utility companies in Malaysia.

Figure 2.2 The electricity utility companies in Malaysia

The conventional power system generally comprises three sections: generation, transmission and distribution. The centralised power generation system allows only unidirectional power flow which is from a higher voltage level to a lower voltage level. At present, electricity is generated in power plants which are located far away from the consumers. The step-up transformers at the generation side step up the network voltage to minimise the transmission losses during the power transmission stage. The electricity from the transmission network will then be stepped down at the substation before being supplied to the low voltage distribution network.

The voltage rating of the Malaysian low voltage distribution network's voltage is 415 V for three phase system and 230 V for a single phase system. The frequency of the system is regulated at 50 Hz with a tolerance of ±1%. The Malaysian low-voltage distribution network is practicing a three-phase 4 wire system with the TT earthing arrangement. TT earthing involves grounding of the transformers' neutral points to ensure the effective operation of the protection system (Tenaga National Berhad, 2011). A complete and well-designed protection and grounding systems can ensure the safety of the system.

2.3 Renewable Energy Sources in Malaysia

Subject to the importance of achieving energy sustainability, the Malaysian government has taken numerous measures to advocate the usage of renewable energy. The Malaysian government had initiated the utilisation of renewable energy as the fifth fuel resource including PV, mini hydro, biomass, biogas and municipal waste under the Small Renewable Energy Programme (SREP) in the 8th Malaysia Plan (The Economic Planning Unit, 2001; Lim et al., 2008). The emphasis on renewable energy is further enhanced in the 9th and 10th Malaysia Plans with the introduction of Renewable Energy Act 2011 (Adham et al., 2014). Under this Renewable Energy Act 2011, feed-in tariff (FiT) mechanism is implemented to allow individuals to opt and sell the power generated from renewable energy sources.

Malaysia is one of the countries that had ratified the Kyoto Protocol. The Kyoto protocol is an international agreement introduced under the United Nations Framework Convention on Climate Change (UNFCCC) in the year 1997 to reduce greenhouse gas emission to the atmosphere. The Clean Development Mechanism (CDM) is proposed under the Kyoto Protocol to allow developing countries to invest in sustainable development projects that reduce greenhouse gases emissions (United Nation, 1998). As a result of that, there are several environmental friendly architectures that comply with the green building index. A recognised green rating system introduced by the Malaysian government for buildings to promote a sustainable built environment and to raise public awareness (Green Building Index, 2013) have been designed and constructed in Malaysia. This is another effort by the Malaysian government in advocating a sustainable environment and to reduce the impact of greenhouse gases emission.

With the increased number of renewable energy capacity installed on the Malaysian distribution network, the amount of greenhouse gas emission contributed by fossil fuel combustion for power generation has decreased tremendously over the past few years. Figure 2.3 shows that the amount of CO_2 gas emission avoided in Malaysia has demonstrated a significant increase from 98334.54 tonnes/ MWh in the year 2012 to 745,810.75 tonnes/ MWh in the year 2015 with an increased number of clean electricity generation from the renewable energy sources (SEDA, 2014b). There are several types of renewable energy sources available in Malaysia, including solar PV, wind, hydro, biomass and biogas.

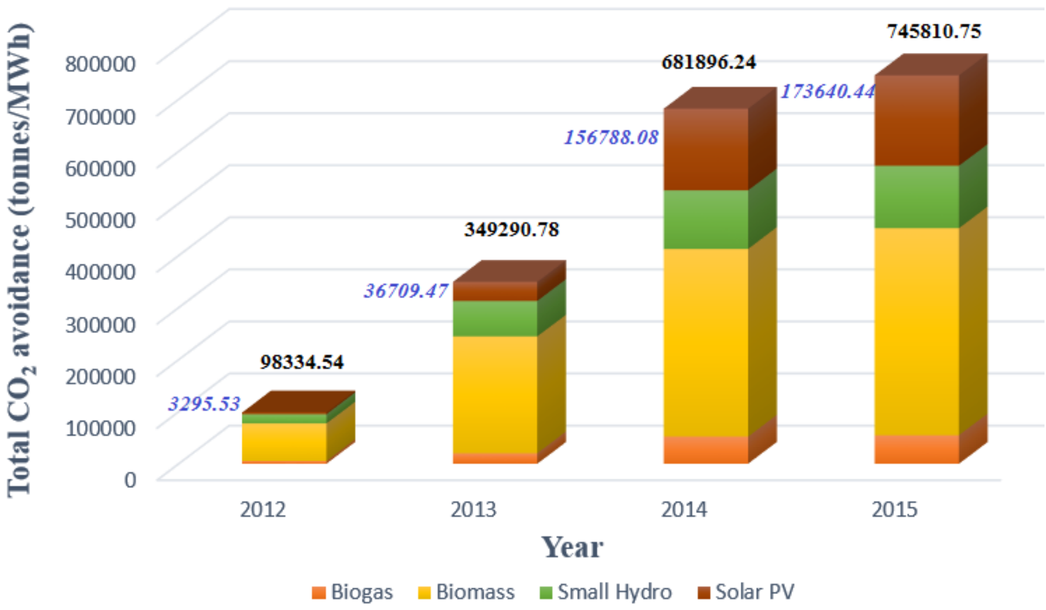


Figure 2.3 CO_2 gases avoidance in Malaysia

2.3.1 Solar Energy

The solar energy can be used for heating purposes and also generating electricity. Solar cells are used to convert sunlight to electrical energy through the photoelectric effect. The power output delivered from the solar cell is directly proportional to the solar irradiance. The PV module cascades several PV cells with a supporting structure to produce a higher output. A power electronic based inverter is used to convert the DC output from the solar cells to AC output, at the nominal voltage level before connecting to the utility grid. Nowadays, the PV inverters are designed with a single-stage of DC to AC converter or a dual-stage converter consisting of a DC to DC boost converter and then followed by a DC to AC converter. Figure 2.4 shows the typical PV inverter with single conversion and dual conversion schemes. The advantage of having a DC to DC boost converter inside the PV inverter with dual stage conversion scheme can step-up the input DC voltage level so as to achieve better efficiency (Stallon et al., 2012). Modern PV inverter is usually equipped with a maximum power point tracking (MPPT) system to keep track of the optimal power output throughout the operation.

The PV system has become a favourable renewable energy source over the last decade due to the advantages of minimum GHG emission, high reliability, low operating and maintenance cost. The commonly used market-ready solar cells are made of silicon. The solar cell materials can be categorised into monocrystalline, polycrystalline and amorphous silicon cells. Table 2.1 shows that the monocrystalline PV cells having the highest efficiency among the solar cells. Research results from the National Centre for Photovoltaics also demonstrate that the monocrystalline PV cells can achieve efficiencies as high as 25.0 % (NREL, 2014). However, the price of the monocrystalline PV cells still remains high due to the complicated fabricating process. With the advancement of solar cell fabrication technology and mass production among the manufacturing industries, the price of solar cell is expected to decline in the future as shown by the Swanson's effect (Swanson, 2006). Several large solar farms have been commissioned in Peninsular Malaysia in conjunction to promote the utilisation of clean energy. In June 2014, a 10.25 MW solar farm installed in Gemas, Malaysia has emerged to become the largest grid-connected solar power plant with power generating capacity of 1.2 million kWh per month (The Rakyat Post, 2014). If this trend continues, solar energy will become an economically viable selection of renewable energy sources in Malaysia.

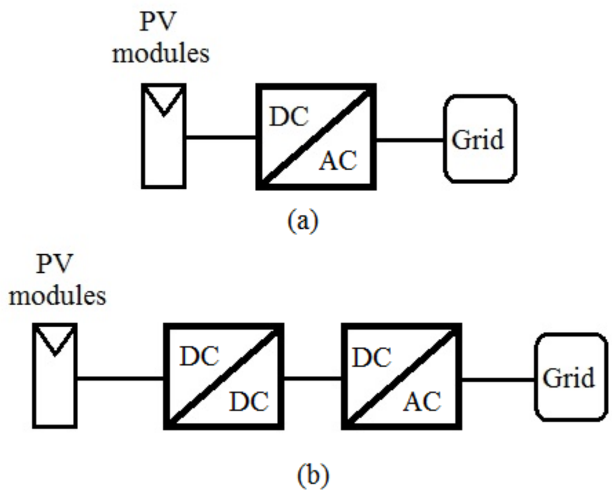


Figure 2.4 PV inverter with (a) single-stage conversion scheme and (b) dual-stage conversion scheme

Table 2.1 Types of commercially available PV solar cells (PTM, 2009)

	Monocrystalline Silicon PV cells	Polycrystalline Silicon PV cells	Amorphous Silicon PV cells
Efficiency	16 – 22 %	12 – 16%	9 – 12%
Cost per Watt (RM/kWh)	4.90 – 8.18	3.27 – 6.54	1.64- 3.27
Reliability	Excellent	Good	Fair

2.3.2 Wind Energy

During the agricultural era, villagers harnessed wind energy with a windmill to power up their water pump or grinding machine. A wind turbine converts the kinetic energy driven from wind power into electrical power (Richardson & McNerney, 1993). Usually, a wind turbine is mounted on a tall structure or on top of the building by taking advantages of faster and less turbulent wind. Most of the modern wind turbines found in the wind farm are using horizontal axis configuration. However, the vertical axis configuration wind turbines have the advantage of harnessing the wind from all directions without the need of relocating the rotor when the wind direction changes. The light composite weight and aerodynamic design of the wind turbine blades are more likely to improve the efficiency of the wind power generation. Figure 2.5 depicts the wind turbines with two different configurations.

A wind controller is used to stabilise the speed of the wind turbine and step-up the DC output. The wind inverter regulates the high input DC voltage into a single phase of 240 V AC source at nominal frequency. The availability of harnessing wind energy in Malaysia is still under research due to inconsistency and relatively low wind speed, which is not more than 3m/s (Aziz, 2011). A typical wind turbine requires a minimum start up speed of 3 to 5 m/s to operate. Simulation studies by Mekhilef & Chandrasegan (2011) had envisaged the potential of building the offshore wind farm in Malaysia due to better wind speed in offshore with fewer obstacles and strong wind availability during monsoons. In future, the Malaysian Sustainable Energy Development Agency (SEDA) is considering to advocate wind energy as another category of renewable energy sources in Feed-in Tariff mechanism.

(a) **(b)**

Figure 2.5 Wind turbine configuration (a) Three bladed HAWT (3.3 MW Vestas) and (b) Darrieus type VAWT (Sandia National Laboratory)

2.4 Renewable Energy Regulatory Framework and Incentives in Malaysia

Legitimate regulatory frameworks need to be established for legal enforcement actions in order to promote the renewable energy utilisation in Malaysia. At present, the total installed capacity of renewable energy sources in Malaysia is still contributing less than 2% of the total electricity generation as shown in Figure 2.1. Therefore, the Malaysian Parliament has enacted the Renewable Energy Act 2011 and Sustainable Energy Development Authority Act 2011 under the 10th Malaysian Plan to provide a more favourable environment to facilitate the growth of renewable energy (The Economic Planning Unit, 2010). Renewable Energy Act 2011 is introduced to enhance the renewable energy growth with this special implementation of Feed-in Tariff (FiT) mechanism. Under this FiT mechanism, owners of the four eligible renewable energy sources, such as PV, hydro, biogas and biomass can opt to sell the generated power to the utility company at a prefixed rate over a specific period (SEDA, 2014c; Johari et al., 2013). Table 2.2 demonstrates the Feed-in Tariff rate with a PV installation in Malaysia offered by the SEDA.

An authorised agency, namely Sustainable Energy Development Authority (SEDA) is established under the SEDA Act 2011 to manage and monitor the progression of FiT mechanism (SEDA, 2011c). SEDA plays an important role in promoting sustainable energy and implementing the national policy related with renewable energy. Under the Renewable Energy Act 2011, an additional 1% of the electricity bill is contributed to the renewable energy fund. This fund is imposed for disbursing the payment for generating renewable energy under the FiT mechanism. The introduced surcharge for the renewable energy fund on electricity bill has increased from 1.0 % to 1.6 % effective from 1st January 2014 for consumer's who consumed more than 300 kWh electricity consumption monthly in order to enhance the renewable energy capacity growth (SEDA, 2014a). Furthermore, a new FiT category has been opened for community-based organisations and places of worship such as mosques, temples and churches to encourage green energy installation (The Star, 2014). The FiT rate for both community-based organisations and residential is the same according to the latest announcement from SEDA as effective on 15th March 2014. Figure 2.6 shows the number of renewable energy installation on the Malaysian electrical network is foreseen to increase gradually with the implementation of the regulatory framework applied by the Malaysian government.

Table 2.2 Feed-in tariff (FiT) rate for solar in Malaysia (SEDA, 2014)

No.	Descriptions	Feed-in Tariff Rate (MYR/kWh)
(a)	Solar photovoltaic installation with capacity of:	
i	Up to and including 4 kW	1.018
ii	Above 4 kW, up to and including 24 kW	0.994
iii	Above 24 kW, up to and including 72 kW	0.850
iv	Above 72 kW, up to and including 1 MW	0.821
v	Above 1 MW, up to and including 10 MW	0.684
vi	Above 10 MW, up to and including 30 MW	0.612
(b)	Solar photovoltaic installation (a) with criteria as follows entitle to have additional bonus:	
i	Use as installations in buildings or building structure	+0.215
ii	Use as buildings materials	+0.207
iii	Use of locally manufactured or assembled solar photovoltaic modules	+0.050
iv	Use of locally manufactured or assembled solar inverters	+0.050

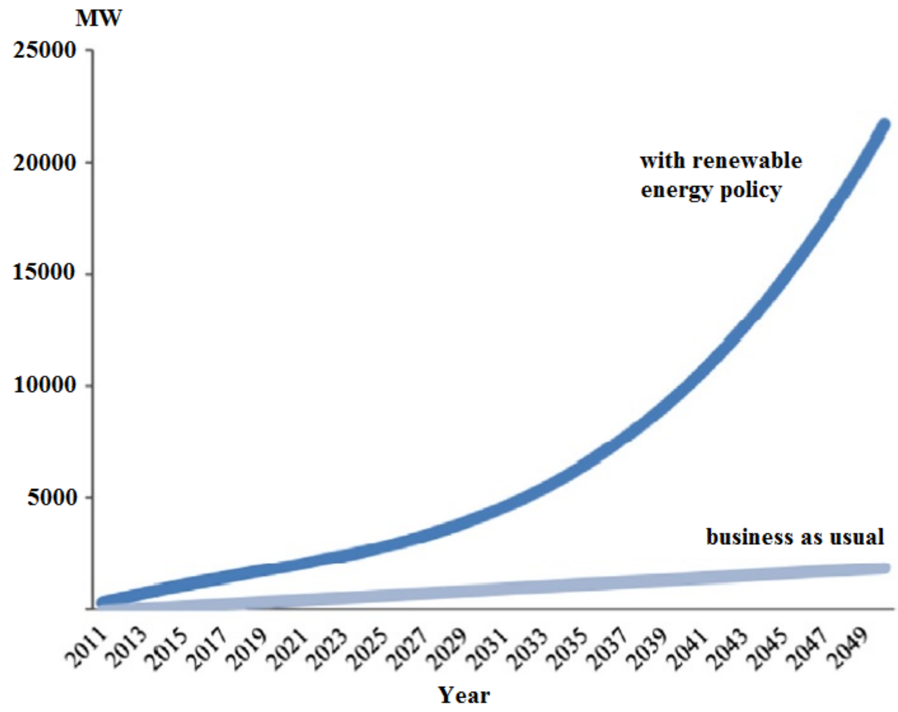


Figure 2.6 The cumulative renewable energy installed capacity in Malaysia (Hanif, 2010)

2.5 International Regulations of Interconnection of Renewable Energy

Several international regulations on the integration of renewable energy into the electrical network have been developed by recognised international agencies such as the Institute of Electrical and Electronic Engineers (IEEE) and International Electrotechnical Commission (IEC). These regulations are established to ensure that the renewable energy are safe and reliable throughout the operating environment once interconnected with the grid. Hence, the installation and design of all grid-connected renewable energy generators need to comply with these regulations. The tolerance level for the electrical parameters such as voltage magnitude, frequency and power quality of the selected regulation are discussed in the following sections.

2.5.1 IEEE 1547: 2003 Interconnecting Distribution Resources with Electrical Power System

IEEE 1547 Regulation, Standard for Interconnecting Distribution Resources with Electrical Power System has emerged to be one of the most prominent standards for interconnection of renewable energy sources. This standard is mainly derived from IEEE 929-2000, Recommended Practice for Utility Interface of Photovoltaic System and UL 1741, Standard for Inverters, Converters and Controllers for use in the Independent Power system, by Underwriters Laboratories Incorporation. The IEEE 1547 standard has specified the technical specification for testing and interconnecting of the system up to 10 MW, which includes the general requirement response to abnormal conditions, power quality events and islanding test specifications. IEEE 1547.3 standard states that the interoperability of one or more distributed resources is interconnected with the electric power system. This standard has delivered the necessary parameters and methodologies for monitoring, data exchange and control of interconnected distributed resources with the power system. All the inverters are required to shut down once the grid is disconnected. The disconnection time is subject to the abnormal condition of the voltage and frequency deviations occurring and will cause the inverter to shut down once exceed the specified range as shown in Table 2.3 and Table 2.4 respectively.

Table 2.3: Disconnection time for voltage deviation

IEC 61727		IEEE 1547	
Voltage range (V)	Disconnection Time (s)	Voltage range (V)	Disconnection Time (s)
< 50 %	0.20	< 50 %	0.16
50% to 85 %	2.00	50% to 85 %	2.00
85% to 110 %	Continue operation	85% to 110 %	Continue operation
110% to 135 %	2.00	110% to 120 %	1.00
>135 %	0.05	>120 %	0.16

Table 2.4: Disconnection time for frequency deviation

IEC 61727		IEEE 1547	
Frequency range (Hz)	Disconnection Time (s)	Frequency range (Hz)	Disconnection Time (s)
49.0 – 51.0	0.200	59.3 – 60.5	0.133

2.5.2 MS 1837: 2010 Installation of Grid Connected Photovoltaic (PV) System

This standard provides a general requirement for the Malaysian grid-connected interconnection of PV systems where the DC open circuit voltage is less than 1000 V_{DC} (MS standard, 2010). This practice also includes the basic requirements and general for design, installation, protection and earthing of the PV system installation. In addition, all the protection system and wiring design are required to be done by the authorised engineer and the installation job is assigned to a certified worker.

Most of the existing standards derived nationwide are incorporated with distributed energy sources. The compatibility of the electrical parameter and disconnection time during loss of main is discussed under existing practices. At present, researchers are still reconciling on creating regulations that allow the renewable energy sources to remain energised during the islanded operation without causing any power quality issues. It has shown that the IEEE technical commission has considered to allow intentional islanding provided that the islanded network has the ability to maintain the voltage and frequency during the islanded operation in IEEE 1547-2008 standard.

2.6 Islanded Operation with Renewable Energy

The islanding term refers to a situation where a portion of the utility network that consists of both load and distributed resources remains energised while isolated from the remainder of the utility system (IEEE, 2000). At present, there are increasing number of anticipated renewable energy sources installed on the distribution network as a result of attractive policies and incentives introduced by the governmental agencies. Once the utility grid is out of service, an islanded network of renewable energy source is conceivable to form. However, all the renewable energy sources are forced to terminate their operation under the existing regulatory framework once isolated from the main grid. Thus, islanded operation of renewable energy sources is not likely to occur prior to safety consideration. One of the main reasons that the islanded operation of renewable energy sources might pose a safety hazard to the working personnel is that the consumer device might operate at voltage and frequency levels outside the permissible range (IEEE, 2011).

2.6.1 Types of Islanded Operation

Islanded operation can be classified as intentional and unintentional. The intentional islanded operation is also known as planned islanded operation. It is usually referred to the scheduled maintenance by the local power provider for voluntarily disconnecting the selected region of the electrical network to allocate servicing and upgrading work. Before isolating from the utility grid, adequate voltage and frequency control on the distribution network is made to meet the power balance between load demand and generation to avoid the large transient occurring during the transition. Numerous simulation studies have been proposed to investigate the feasibility of the intentional islanding on distribution network. Simulation studies by Seca & Lopes (2005) have demonstrated that the potential of intentional islanding with distributed generation can improve the reliability of the distribution network. Another simulation study on intentional islanding is also investigated to improve the reliability of the Brazilian network system (Londero et al., 2010). The impact study on intentional islanding operation with the distributed generation of Thailand's electrical network has been discussed and investigated (Fuangfoo et al., 2007; Fuangfoo et al., 2008). Simulation studies by Enacheanu et al. (2005) have proposed that the intentional islanding operation can prevent a blackout incident. The authors have proposed an algorithm with EUROSTAG simulation software so that a local agent with adaptive voltage and frequency control can be carried out to allow islanding operation of the distribution network. A dynamic simulation study on intentional islanding of the Malaysian distribution network with hydro distribution generation is done with PSCAD (Mohamad et al., 2013). In future, the IEEE technical committee is considering to allow intentional islanding of the electrical power system under specified conditions (IEEE, 2011).

Unlike the aforementioned islanded operation, the nature of the unintentional islanded operation tends to be spontaneous as it can occur at any time and at any place. When a fault occurs in the system, the grid is shut down deliberately from the utility grid without prior notification. In this circumstance, forming an islanded operation with renewable energy sources is unlikely to happen. According to the international regulation, the renewable energy source present in the distribution network is required to disconnect during islanding (Suruhanjaya Tenaga, 2010). Hence, an anti-islanding protection system has been embedded within the power electronic based inverters as stated under the existing regulatory framework as a protective measure when the grid is out of service. Several simulation studies have addressed the potential risk of unintentional islanding operation with the inverter based distributed generation (Caldon et al., 2013; Moghaddam et al., 2012; Sgarbossa et al., 2014). There are several islanding detection methods to be discussed in section 2.8.

2.6.2 Benefits of Allowing Islanded Operation with Renewable Energy

One of the main contributions of islanded operation with renewable energy sources is to ensure the continuity of power supply of the selected network especially during the occurrence of power disruption. Figure 2.7 shows that the total number of power interruptions per 1000 users in Malaysia is 73.53 in the year 2013 (Energy Commission, 2014b). The data indicates that the number of power interruptions in Malaysia is high. The Sabah state has the highest number of power outages in Malaysia, having 49.60 power outages per 1000 users in year 2013 (Energy Commission, 2014b). Therefore, the occurrence of power disruptions event can be reduced if a section of the distribution network has the ability to form an islanded network while exploiting renewable energy sources during the islanded operation. The renewable energy sources can continue to energise the load even without being affected by the power disruption event provided that the voltage and frequency of the islanded network are well regulated. Hence, an islanded operation of renewable energy provides a promising solution to those areas which are struggling with high occurrence of power interruption.

The reliability of the electrical system is always concatenating with the frequency and duration of the power interruptions of the selected region. According to the drafted guide IEEE - P1366, the measures of the system reliability can be determined by the indices such as System Average Interruption Distribution Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). SAIDI is a measurable index of the average power interruption duration for each customer. This index is able to provide the records of the utility company the total average time that the customer's supply being interrupted. SAIFI is a measure of the outage during a year for every consumer.

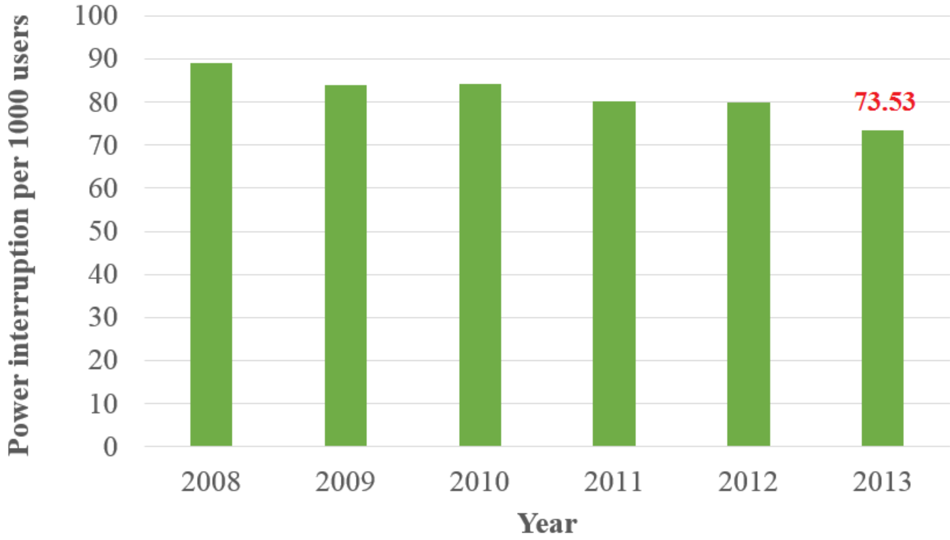


Figure 2.7 Number of power interruption per 1000 users in Malaysia

Equations below show the evaluation for SAIDI and SAIFI respectively.

$$SAIDI = \frac{Sum\ of\ all\ customer\ interruption\ durations}{Total\ number\ of\ customer\ served} = \frac{\sum_{i=1}^{n} C_i d}{N} \quad (2.1)$$

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customer\ served} = \frac{\sum_{i=1}^{n} C_i}{N} \quad (2.2)$$

where c_i is the total number of interrupted customers

d is the restoration time of each interruption event

N is the total number of customers served

n is the total number of interruption events

Figure 2.8 shows that the SAIDI for TNB in Peninsular Malaysia is 64 minutes per customer in the year 2012 (IEA world energy, 2012). Even though the indices show that the electricity supply in Malaysian is considerably stable as compared to some other developed countries, however there are still some areas located in Sabah that have high SAIDI and SAIFI values as shown in Figure 2.9 and Figure 2.10. This can create a high level of discomfort among customers. Hence, if the section of the distribution network has the ability to operate the islanded network during power outages with a stable frequency and voltage level, the reliability of the power system can be further strengthened (Nourai & Kearns, 2010; Junlakarn & Ilic, 2014).

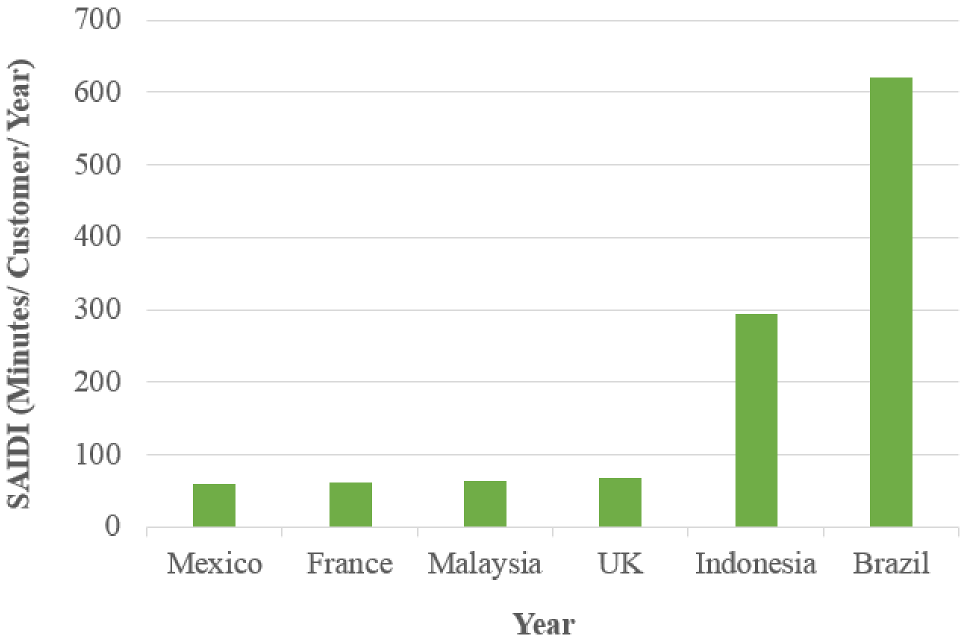


Figure 2.8 SAIDI of selected country in year 2012

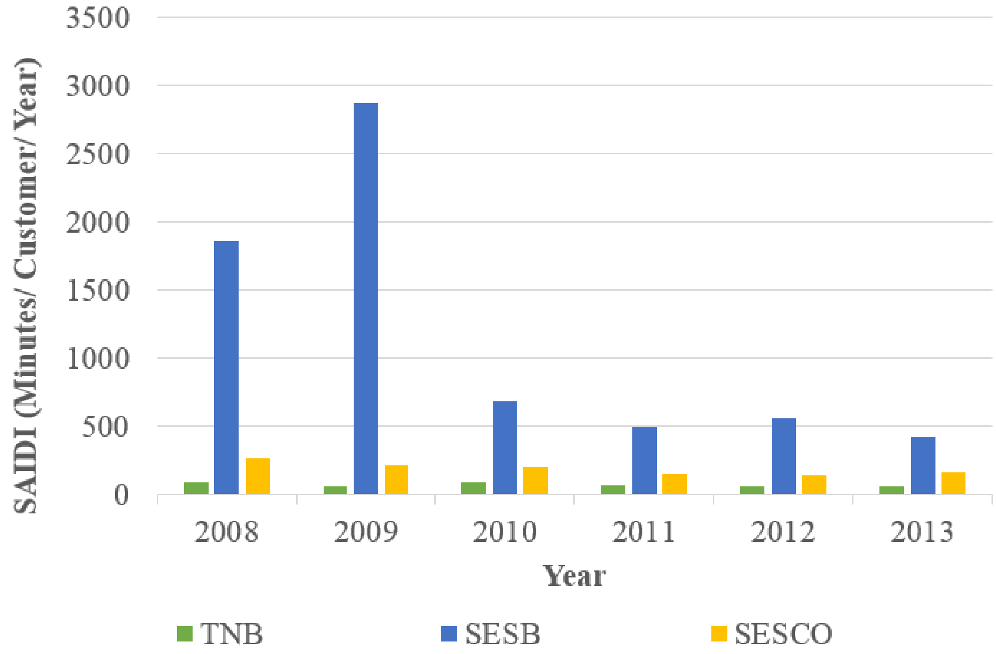


Figure 2.9 SAIDI of the three main power provider in Malaysia

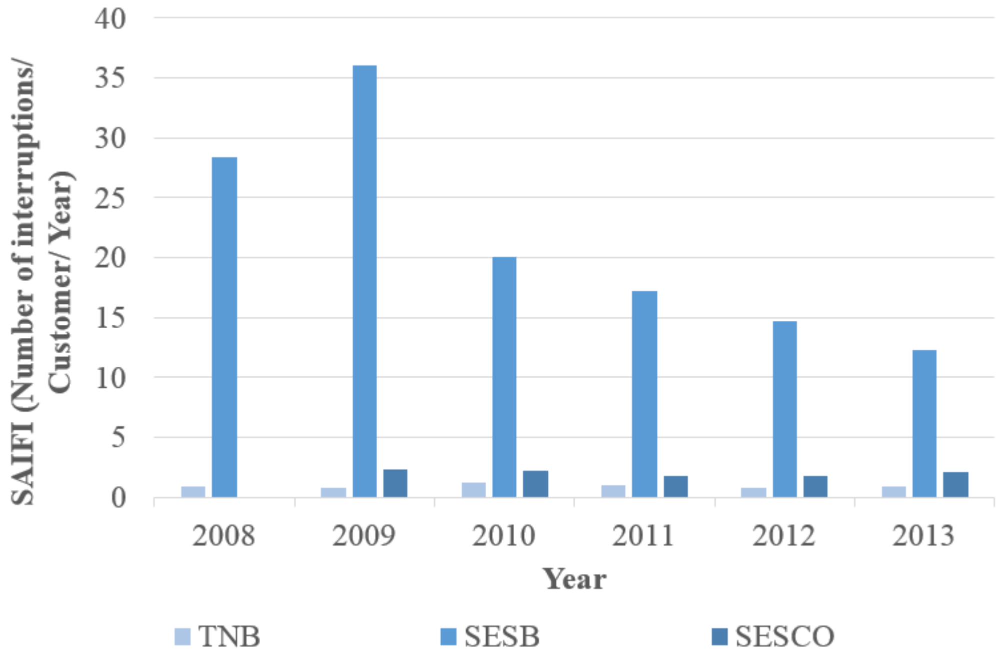


Figure 2.10 SAIFI of the three main power provider in Malaysia

Power restoration after a huge electrical breakdown can be a time-consumable process and some might take up to several months when dealing with poor weather condition and lack of technical support. Thus, this can lead to dissatisfaction among end-users. When there is a fault on the utility grid, all renewable energy sources are forced to shut down as stipulated by the existing regulation framework. Therefore, the customer might not be able to benefit from solar energy or wind energy after isolated from the grid even under a good weather condition. Simulation studies have shown that the utilisation of renewable distributed generation can improve the duration of power restoration (Neto et al., 2006; Pham et al., 2009). However, when there is a proper control of voltage and frequency present within the islanded network, the renewable distributed generation can stay online and continue to energise the load without tripping off by the anti-islanding protection system. Thus, this provides an opportunity for the end-user to continuously utilise the renewable energy and will not be affected by the occurrence of the islanded operation.

In addition, the amount of greenhouse gases emission can be reduced with the utilisation of renewable energy sources. Figure 2.11 shows the amount of greenhouse gases to be avoided over 30 years at various locations in Malaysia with PV systems installed (Lim et al., 2008). Thus, with the increased number of renewable energy sources installed on the distribution networks, it is possible to review the feasibility of the islanded operation of PV systems.

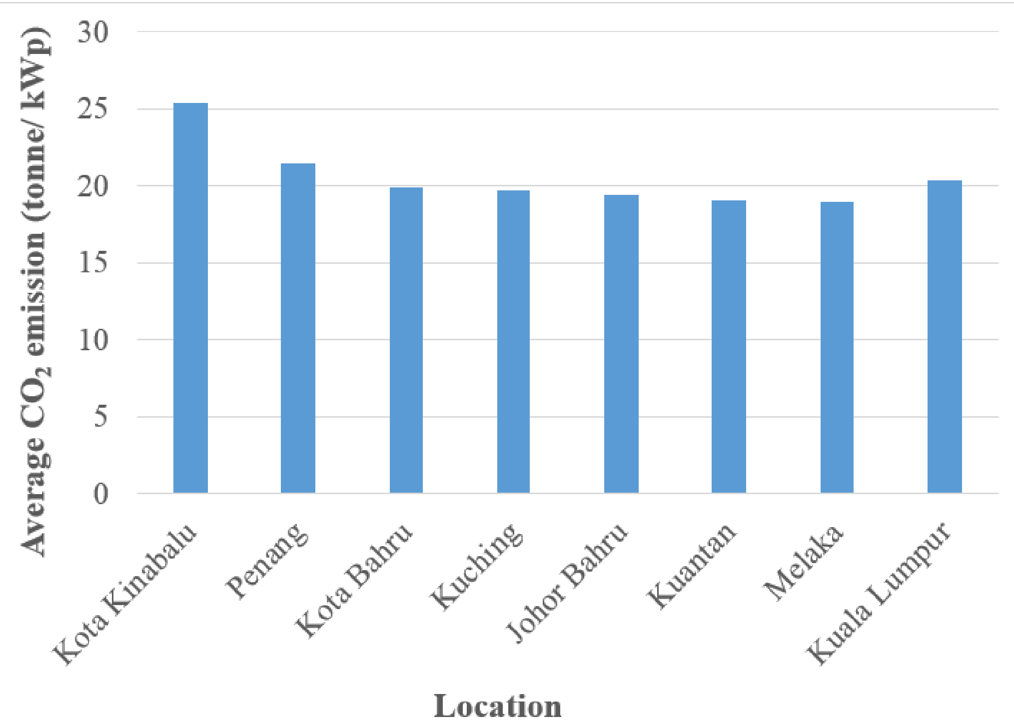


Figure 2.11 The amount of CO_2 gases to be avoided over 30 years at various locations in Malaysia (Lim et al., 2008)

2.6.3 Technical Aspects of Allowing Islanded Operation with Renewable Energy

At present, the conventional electrical power system is designed to allow the unidirectional power flow hierarchically from the upper stream of the transmission terminal to the consumer load downstream. Nowadays, the integration of renewable energy sources on the distribution network has changed the existing power flow into a bi-directional direction. Therefore, several concerns need to be taken care in order to ensure the stability of the electrical network during the islanded operation of renewable energy.

2.6.3.1 Voltage and Frequency Regulation of the Islanded Network

An adequate voltage and frequency regulation of the distribution network can ensure a stable operation of the electrical system. During a grid-connected operation, the utility grid governs the voltage and frequency of the network to stay within the statutory limits. According to the Malaysian International Electrotechnical Commission MS IEC 60038: 2006 standard, the steady state voltage of the low-voltage distribution network should be kept at +10% and -6% of the nominal voltage of 230 V while the low-voltage distribution network frequency needs to be maintained at ±1% with the reference of 50 Hz. Any voltage and frequency beyond these statutory limits can create power quality issues in the electrical network such as voltage rise and voltage dips that can potentially damage the consumer equipment. Once the network is isolated from the grid, the voltage and frequency regulation of the islanded network is no longer maintained by the grid. Thus, there must be a mechanism present in the islanded network to have the ability to keep the voltage and frequency within the permissible range. It is mandatory to have proper control of the voltage and frequency to ensure the stability during grid-connected operation and also islanded operation (Chandrakar et al., 2012).

2.6.3.2 Earthing the Neutral Point of the Islanded Network

Under the existing practice, all the grid-connected renewable energy sources are allowed to operate even without an earthed neutral point in Malaysia. The TT earthing system is normally practised in the Malaysian distribution network, where the neutral point of the low-voltage distribution network is earthed at the transformer side when it is connected to the utility grid. However, the neutral point of the islanded network might not be properly earthed once the utility grid is isolated. If the neutral point of the islanded network is not earthed, the protection system on the islanded network may not operate when a fault occurs. Therefore, there are several methods to create a grounded neutral point in the islanded network. The first approach to create a neutral point connection is by using a zig- zag transformer. Figure 2.12 shows the layout of a zig- zag transformer with an interconnected star configuration that can maintain the neutral point near to ground potential. The use of the zig-zag transformer can also reduce the harmonics and neutral current of the islanded network (Jou et al., 2005). Another technique to earth the islanded network neutral point is by using an interlocking contactor. The interlocking contactor will be activated so that the neutral point will be earthed once isolated from the grid in order to complete the electrical connection of an islanded network.

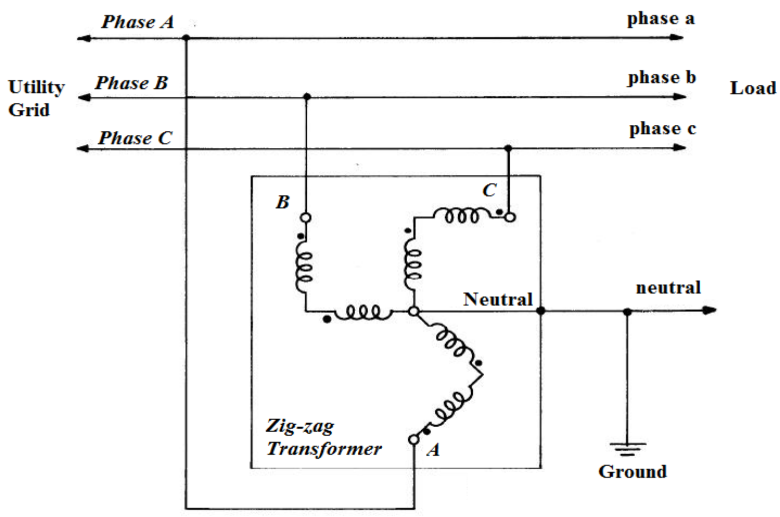


Figure 2.12 System configuration of the zig-zag transformer (Source: http://navalfacilities.tpub.com/hdbk419a_vol1/hdbk419a_vol10137.htm)

2.6.3.3 Synchronisation of the Islanded Network

Another important aspect during the islanded operation with renewable energy are to synchronise the islanded networks to the grid. A synchronisation procedure is required to reconnect an islanded network with the main power grid after the fault is cleared. The isolated network is not synchronised with the utility grid during islanded operation. Before reconnection with the utility grid, electrical parameters such as frequency, voltage magnitudes and phase angles of the islanded system and grid are measured so that they are closely matched. This practice can prevent a large current of in-rush flowing into the islanded network during reconnection with the grid which is likely to cause damage to the customer's equipment. A synchronising check or Sync check relay is widely used to check the synchronisation during reconnection of the islanded network with the utility grid. Nowadays, there are specially designed hybrid inverters that are featured with a synchronising equipment to automatically match with the grid voltage and frequency level so that it can operate both at grid-connected operation and islanded operation.

2.7 Methods for Voltage and Frequency Regulation of the Islanded Network with Renewable Energy

In a small electrical system, a slight deviation in power difference can cause a frequency excursion to exceed the permissible range. A proper voltage and frequency regulation of the islanded network with renewable energy sources can be challenging. Furthermore, it is also a challenge to create a synchronism between renewable energy sources and the grid-forming unit during the islanded operation to avoid out of synchronism. At present, there are mainly two approaches that are applicable to maintain the voltage and frequency of the islanded network. The first approach is by utilising rotating based machines including synchronous generator and induction generator which are controlled by a governor system. Another method is by adopting energy storage systems with power electronic based controller to regulate the voltage and frequency of the islanded network after isolation. Numerous studies have been carried out recently to understand the behaviour and characteristics of the islanded operation.

2.7.1 Rotary Based Machine for Islanded Operation

Islanded operation with a local generator is one of the techniques to provide voltage and frequency regulation. Rotary based machines such as diesel generator are widely applicable to serve as a backup power unit to provide an uninterruptible supply of electricity in a small island network. Diesel generators are selected to operate in islanded networks due to its ability to maintain a stable operation of a small electrical network and also capable to provide voltage and frequency reference to the renewable energy sources. The operating principle of the diesel generator is quite similar to the large generator in a power station. The frequency of the network varies according to the rotational speed of the generator while the voltage of the network is determined by the changing magnetic flux of the rotating machine winding (Kundur, 1994). A simulation study by Du et al. (2001) has designed a state detection algorithm using DigSILENT software to investigate the characteristics of the islanded operation with a gas turbine generator. The authors illustrated that the proposed algorithm is able to alter the generator's control according to different operating modes. The behaviour of the gas turbine generator with governor control during the transition from grid-connected to islanded operation is studied by Mahat et al. (2006). Best et al. (2007) have proposed a phase difference control governor system to be integrated into a diesel powered generator in maintaining synchronism during the islanded operation. In Thailand, research studies in the real distribution system have been carried out to study the feasibility of islanding operation with mini-hydro generation. The study was tested at the Namman and Namsan power stations that were connected to the distribution network (Tantimaporn et al., 2010). If the rotary based machine can maintain the voltage and frequency within the statutory limits, then the renewable energy sources might not shut down and cease energising the load during islanded operation. However, fossil fuel based rotary based machine seem to be a non-environmental friendly selection for islanded operation as it will emit greenhouse gases during fossil fuel combustion. In addition, the inertia characteristics of the rotating based machine can cause a slow response during transition across two different operating modes. Hence, new technology driven by power-electronic devices with energy storage system has been evolved to provide a better selection to allow the formation of islanded networks.

2.7.2 Application of Energy Storage in Islanded Operation

At present, numerous types of energy storage systems are available in the market. The size of the energy storage system can be scaled from a small household usage of a few kilowatts up to several gigawatts for industrial applications. The selection of appropriate type and size of the energy storage system can ensure the reliability of the selected network at an optimal cost (Smith et al., 2008; Smith et al., 2010). A battery based energy storage system can be easily found in the market nowadays. This electrochemical based energy storage system which includes lead acid batteries, lithium ion batteries and Nickel Metal hydride (Ni-MH) batteries. Battery technology has been utilised in a wide area of applications ranging from short-term power quality support to long-term energy management. Lead acid battery is among the oldest energy storage system available in the market with its technology proven for more than a century. The advantages of lead acid battery is that it is cheap and suitable for low cost applications. However, lead acid battery is heavier and bulkier as compared to the other types of electrochemical based energy storage system. Super-capacitor is an energy storage technology which stores the charge on the electrochemical double layer capacitor plate. This highly reversible energy storage has a fast charging and discharging capability, but having a lower power density. A flywheel stores up the kinetic energy in a high speed rotating wheel. The quick response of the flywheel up to tens of thousands of cycles per year allows this energy storage technology to mitigate power quality issues (Lazarewicz & Rojas, 2004). Table 2.5 summarises several types of energy storage technologies with their pro and demerits respectively.

Table 2.5 Summary of the available energy storage system technology

	Advantages	Disadvantages
Lead acid batteries	- Low cost - Efficiency at 80-90 %	- Shorter life span - Heavy and bulky
Lithium ion batteries	- High energy density - Longer life span	- High cost
Nickel Metal Hydride (Ni-MH) batteries	- Reliable and durable - Long life cycle	- High maintenance
Flywheel	- Quick response -	- High self-discharge - Low power density
Super-capacitor	- Dependable - Highly reversible	- Low power density

The energy storage system has been used to ensure an uninterruptible power supply to the critical load during power outages in places such as hospitals and government buildings. The use of an energy storage system to regulate the voltage and frequency in an islanded AC network is presented with the use of droop controlled inverter (Wasynczuk, 2012). The use of an energy storage system in frequency regulation of the DC coupled isolated system is also studied by Singh et al. (2014). Other than that, battery based storage shows a great potential in the frequency regulation in a small network. A simulation study by Rajesh & Kumar (2012) has shown that the effectiveness of the battery in mitigating the frequency fluctuation in a small isolated network. Batteries can provide an immediate response at around 20 ms to compensate the power imbalance after isolation (Chauhan & Saini, 2014). The integration of capacitors can improve the transient response during the islanding operation of an electrical distribution network (Johnston, 2013).

Energy storage systems are also capable of providing an effective approach to mitigate the intermittent power output without curtailing any renewable energy. Numerous studies have been proposed that the energy storage system can be used in mitigating power fluctuations cause by wind generation (Atwa & Saadany, 2010; Teleke, 2010; Chen et al., 2011). Other than that, the integration of the energy storage system into the distribution network can provide peak shaving during peak hours to reduce the electricity bills and for arbitrarily (Rahimi et al., 2013). A 1 MW battery energy storage system has been installed and tested in Zurich where it is controlled with the developed peak shaving algorithm (Koller & Vollmin, 2013). In another study, the author has issued the benefits of implementing an energy storage system by storing the excess power generated from the PV system (Hung et al., 2014). A simulation study by Singh et al. (2014) with a proposed phase shift controller illustrated the feasibility of battery based storage in mitigating the power fluctuation caused by the PV system.

The energy storage system equipped with a power electronic based controller can also be used to provide voltage and frequency regulation in order to allow the islanded operation with renewable energy. During grid- connected operation, the frequency and voltage of the network are governed by the main grid. However, when a section of the network is isolated from the main grid, the controller will switch from grid-connected mode to voltage and frequency (V-f) control mode. There must be at least one master unit present in the islanded network to provide the voltage and frequency reference so that the distributed generation can remain operated even after the grid is out of service (Lopes et al., 2006). Numerous studies on software modelling of power-electronic based controller of energy storage system with two different control strategies are introduced by the researchers. The authors have proposed a controller with two various controls: current control mode during grid-connected operation while islanding operation with voltage control mode are proposed to ensure voltage and frequency stability during the islanding operation (Balaguer et al., 2011; Sedghisigarchi, 2011). On the other hand, a power electronic controller modelling is developed with two operational modes: active and reactive power control (P-Q) control mode by injecting or absorbing power to the grid at grid-connected operation and V-f control mode during islanded operation mode (Caldon et al., 2004; Kamel et al., 2011).

In addition, several studies have been studied by researchers on the PV system and battery hybrid electrical network. Kottick et al. (1993) has studied that the integration of a battery energy storage system into the hybrid electrical network can provide better dynamic performance during the transition and improve the reliability of the power supply. Simulation studies have been carried out on a proposed new control method to allow islanded operation on a hybrid network consists of PV and diesel generator (Mishra et al., 2011). In addition, a frequency droop based virtual synchronous generator method on voltage source controller power electronic based controller is proposed by the authors to allow the islanded operation (Du et al., 2013).

2.8 Islanding Detection Methods

Fast and reliable islanding detection systems are introduced to indicate the occurrence of an islanding event. Numerous islanding detection methods have been developed and embedded into power electronic devices to shut down the renewable energy sources once isolated from the grid. Inadequacy to disconnect the inverter during an islanding event can lead to severe damage on the consumer’s side. Therefore, the effectiveness of an islanding detection method can be evaluated by using the non-detection zone (NDZ) as shown in Figure 2.13. The NDZ can also be treated as a performance index for evaluation of the islanding detection methods (Ye et al., 2004; Fan & Li, 2011; Bahrani et al., 2011; Ghaderi & Kalantar, 2011). NDZ is a region formed by the power mismatches between load and generation that occurs at the inception of islanding. This is the boundary where the islanding detection method is unable to detect the occurrence of an islanding event. Thus, it is possible for the renewable energy sources to remain operated when the voltage and frequency values stay within this region. The islanding detection method with a smaller NDZ is more favourable to obtain a better performance in detecting an islanding event.

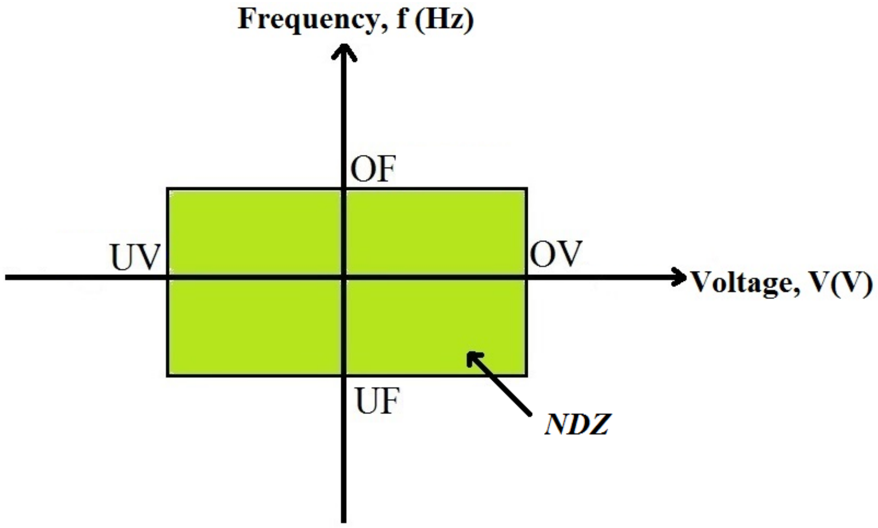


Figure 2.13 Non-Detection Zone (NDZ)

The islanding detection method can be classified into remote and local techniques. The remote technique requires communication with the utility sides, therefore an additional communication device is installed to monitor and feedback the electrical parameter reading to the utility. The benefits of this method are having zero NDZ and do not undergo power quality degradation, but are relatively expensive as compared to the local techniques. The local technique usually is embedded within the power electronic device. It can be subdivided into three groups: passive, active and hybrid. The passive method detects the changes on the electrical parameters such as voltage and frequency at the point of common coupling (PCC) during islanding. This method is rather simple and easy to be implemented. Thus, it is more suitable for low-cost applications (Ahmad et al., 2013). The active method injects a small perturbation at the PCC to force changes in the electrical parameter to enhance the islanding detection capability (Liu et al., 2010; Bahrani et al., 2011). This method can create a smaller NDZ, but can cause power quality deterioration. Next, the hybrid method which combines the advantages of both active and passive method can obtain a negligible NDZ. However, the design and structure of this method appears to be much more complicated as compared to the other local methods. Figure 2.14 depicts the overview of the islanding detection methods. The commonly used islanding detection methods such as Over-Under Voltage (OUV) and Over-Under Frequency (OUF), Phase Jump Detection (PJD), Active Frequency Drift (AFD), Slip Mode Frequency Shift (SMS), Supervisory Control and Data Acquisition (SCADA) and Power Line Carrier Communication (PLCC) are further discussed in the following sections.

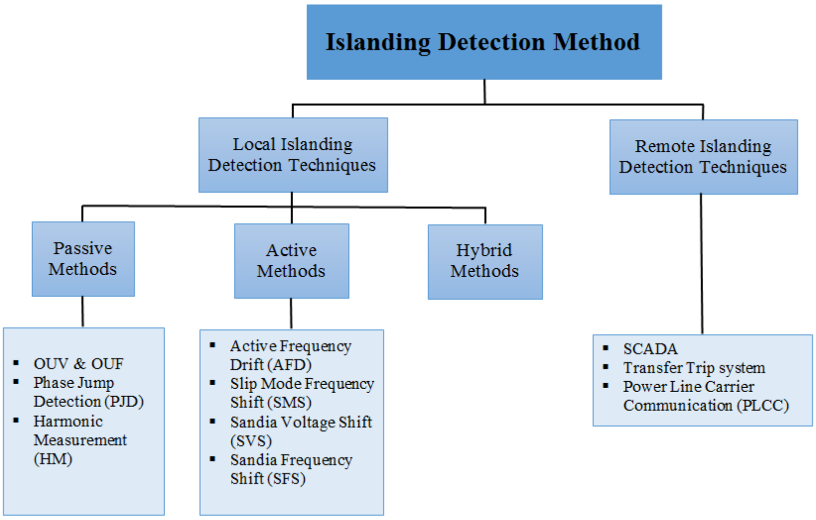


Figure 2.14 Islanding detection methods

2.8.1 Over – Under Voltage (OUV) and Over – Under frequency (OUF)

Over – Under Voltage (OUV) and Over – Under Frequency (OUF) methods monitor the voltage and frequency variations at the PCC. Nowadays, this passive method is one of the most fundamental and widely applicable islanding detection methods used in modern power electronic inverters (Khamis et al., 2013). When the voltage or frequency of the network is outside the predefined threshold, it will activate the protection mechanism such as a relay is triggered to disconnect the inverter's operation (Zhu et al., 2009). The advantages of OUV and OUF method are low cost and will not degrade the power quality of the network. However, the primary drawback of this islanding detection method is having a large NDZ.

2.8.2 Phase Jump Detection (PJD)

Phase jump detection (PJD) method is a passive method that monitors the phase difference between the terminal voltage of the distribution network and the inverter output current. This method can be easily implemented using zero-crossing detection method with a phase lock loop to update the phase angle in each and every cycle (Bower & Ropp, 2002). The rapid change in the phase angle is used to indicate the occurrence of an islanding event. This method does not affect the power quality of the network and tends to have a smaller NDZ as compared to the OUV and OUF method. However, this method might not be able to detect the occurrence of islanding in the case of small power mismatch between the load and inverter. Thus, it is important to carefully determine the threshold value in order to prevent nuisance tripping that caused by switching transient (Hanif et al., 2011).

2.8.3 Active Frequency Drift (AFD)

Active frequency drift (AFD) method injects a perturbation to slightly distort the current waveform (Ropp et al., 1999; Geng et al., 2010). Thus, the current's frequency waveform will be drifted away from the voltage's frequency waveform once the grid is isolated and causes it to exceed the OUF threshold. This method can be easily implemented to the power-electronic based inverter. However, this method is not so effective when a large reactance is present at the load. The NDZ can hardly be minimised to zero when having a poor quality factor, Q_f of the LC load where the reactive load is present (Lopes & Sun, 2006). Hence, several studies have discovered that this islanding detection method can be implemented by using the active frequency drift with positive feedback or Sandia frequency shift. This improved method can achieve the smallest NDZ among the active islanding methods (Bower & Ropp, 2002).

2.8.4 Slip Mode Frequency Shift

Slip mode frequency shift (SMS) is an active islanding detection method which applies a positive feedback to shift the voltage phase angle at the PCC by destabilising the short-term frequency (Smith et al., 2000; Hanif et al., 2011). This islanding detection method is similar to the active frequency drift method. When the PV inverter operates at zero current-voltage phase angle under a nominal frequency during grid-connected operation. A phase-locked loop (PLL) is integrated into this method to stabilise the system frequency when the grid is present. Once the network is isolated, the PLL is no longer able to tune back the frequency and cause it to drift away. The phase angle difference between the current and voltage is formed. The instability of the system frequency is further amplified until it exceeds the OUF threshold and subsequently turns off the inverter (Bower & Ropp, 2002). The performance of the SMS can be easily implemented with software to have a smaller NDZ and faster disconnection time during islanding. Similar to other active detection methods, the introduction of perturbation will deteriorate the power quality of the system. Liu et al. (2009) have proposed an additional phase shift to the existing SMS, namely improved-SMS so that the performance of the SMS can be improved with a smaller NDZ.

2.8.5 Supervisory Control And Data Acquisition (SCADA)

The Supervisory Control and Data Acquisition (SCADA) system monitors the status of each circuit breaker that could cause the occurrence of islanding. This remote islanding detection method is highly effective and it will not degrade the network's power quality (Ahmad et al., 2013; Khamis et al., 2013). Additional communication devices and sensors are installed to monitor the electrical parameters including voltage and frequency on inverter devices. The SCADA system is used to coordinate with the main central control which gathers all the data from the field sensors and processes it into useful information to allow for immediate response once disconnected from the grid. The transfer trip system is incorporated with the SCADA system by sending a signal to disconnect the inverter immediately once the islanded region is identified (Chandrakar et al., 2012). The SCADA system is suitable for large scale distribution networks above the substation level as it has zero NDZ. However, the complexity of the SCADA design and high implementation costs makes this method not suitable for small-scale residential users.

2.8.6 Power Line Carrier Communication (PLCC)

This method uses a low energy communication signal along the power line between the transmitter located at the grid side and a receiver which is installed at the PCC on the consumer side. The continuous low frequency signal is required to propagate from the utility grid to the consumer side without any obstacles. When the communication signal is interrupted, the receiver no longer receives the signal from the transmitter (Ropp et al., 2000; Xu et al., 2007). Hence, this indicates that the continuity of the line has broken and will immediately cause the inverter to cease operation. This method can be implemented to detect islanding on the network with multiple inverters installed in parallel by having zero NDZ without any power quality degradation. However, the additional installation cost of the transmitters and receivers have made this method to be an uneconomical selection for the low-voltage level customers. Table 2.6 summarises the pros and cons of the aforementioned islanding detection methods.

Table 2.6 Summary of the specified islanding detection methods

	Advantages	Disadvantages
OUV & OUF	- Low cost - Easy to implement	- Large NDZ
	- Low cost	- Nuisance tripping
AFD	- Smaller NDZ - Easily implementation	- Power quality degradation
SMS	- Smaller NDZ - Improved disconnection time	- Power quality degradation
SCADA	- Zero NDZ - Highly reliable	- High implementation cost
PLCC	- Zero NDZ	- Additional communication devices required

2.9 Summary

The Malaysian government has introduced a series of new incentives related to renewable energy installation in order to promote the usage of renewable energy and to reduce the greenhouse gases emission. It is not surprising that the burgeoning PV installation in Malaysia will continue to increase in the future. Hence, PV power generation provides great potential as a renewable energy source in Malaysia. With the increasing number of PV systems installed on the distribution network vicinity, this will increase the stress on the utility grid and likely to create an islanded operation with PV systems when a fault is present in the utility grid. However, all the grid-connected renewable energy sources will cease operation once isolation comes under the existing regulatory framework. Various islanding detection methods are introduced to protect the equipment during the islanding event. Conducting islanded operation of PV systems on the distribution network is proposed to provide a solution to cope with the high occurrence of power disruption events. When the distribution network has the ability to form an islanded network, the continuity and reliability of electricity in the selected network is secured. Furthermore, the end-user can continue to utilise the green energy powered by PV systems during the islanded operation. With the advancement of energy storage system technology, the price is expected to drop in the future. Thus, this provides an opportunity to allow the islanded operation with PV system with the use of bi-directional inverter coupled with batteries. Lead acid batteries have been selected as the energy storage technology for my research studies due to costing aspects.

CHAPTER 3

EXPERIMENTAL BUILT-UP FOR THE ISLANDED OPERATION WITH PV SYSTEMS

3.1 Introduction

An experimental low voltage distribution network was designed to provide a platform for investigating the viability of conducting the islanded operation of PV systems. The integration of an energy storage system into the experimental distribution network is to evaluate the feasibility of islanded operation of PV systems. In this chapter, the design and details of each component of the laboratory scale low voltage distribution network are presented.

3.2 Construction of the Low Voltage Distribution Network

An experimental low-voltage distribution network was formed by coupling a 15 kVA synchronous generator coupled with an induction machine which was driven by a variable speed drive as shown in Figure 3.1. The variable speed drive was used to maintain the network frequency at 50 Hz throughout the operation. The reference speed of the synchronous machine can be easily manipulated at a variable speed drive to obtain different operating frequencies. The constructed experimental low-voltage distribution network had a radial three-phase four wire topology and a highly resistive network impedance. The experimental network uses TT earthing system which is the common practice in the Malaysian distribution network.

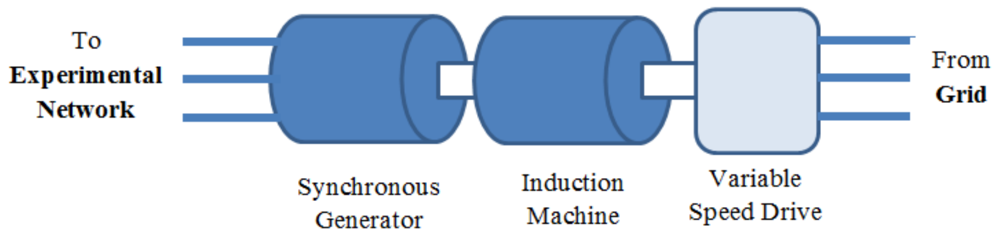
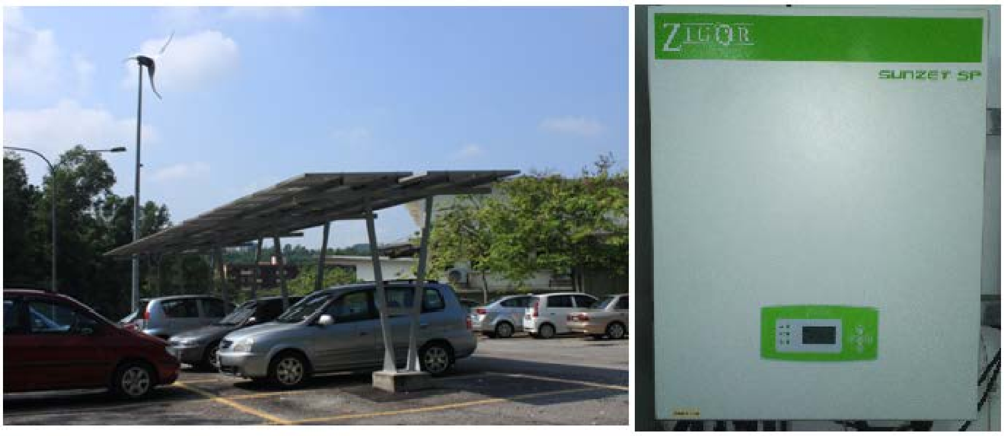


Figure 3.1 Layout of the grid emulator

3.3 PV System

Each 3.68 kW_p PV system consisting of 16 PV modules manufactured by Panasonic is connected to a 3.6 kW DC-AC PV inverter. Each of these polycrystalline PV modules (Model number: VBMS230AE01) can produce a nominal output of 230 W. A power electronic based PV inverter was used to convert the DC input from the PV modules into a sine wave AC sources at 240 V output. Two PV systems can produce a total power of 7.2 kW_p. Both PV systems were commercially available products that had complied with the international standards. 32 PV panels were installed at the university car park area and faced toward the north at a tilt angle of 5^o to let the rainwater to flow out. Other than that, any dust on the PV panels can be washed away easily by the rain water. Figure 3.2 (a) shows the PV panels supported with a 3.3 metres height metal structure. The Spanish manufactured Zigor PV inverter was placed at the laboratory as shown in Figure 3.2 (b).



(a) (b)

Figure 3.2 (a) PV panels supported by a 3.3 metres high metal structure at the University car park area (b) Spanish made PV inverter from Zigor

3.4 Load Emulator

The load emulator consisting of 18 power resistors was designed to mimic the customer's power consumption. Figure 3.3 depicts two units of load emulators. Each of the 500 W power resistive load was activated by a solid state relay. The solid state relay with silicon controlled rectifier output was controlled by the National Instrument's 32 channels digital input/output series module, NI 9403 which was used to translate the load emulator data to digital data. The translated digital data was used by the supervisory computer which was controlled using LabVIEW™ control algorithm. Figure 3.4 shows the controllable load emulator of the experimental network. A controllable load bank was used to vary the load in steps of 500 W up to a total power of 9.0 kW in the single phase configuration under nominal voltage conditions.

Figure 3.3 Load emulator installed at the laboratory

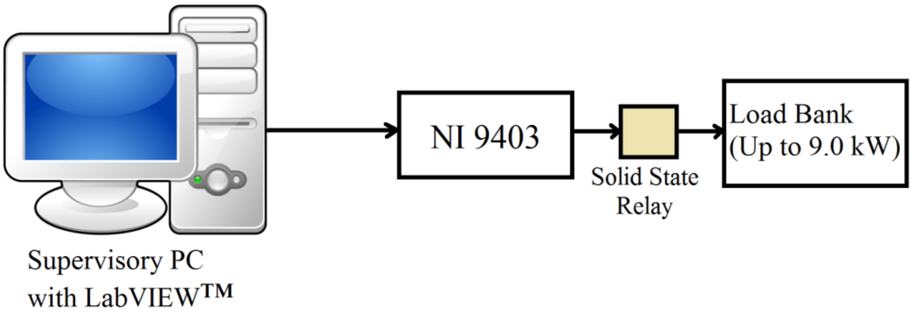


Figure 3.4 Controllable load emulator

3.5 Bi-Directional Inverter

A 5 kW rated power bi-directional inverter coupled with batteries was integrated on the experimental network. This inverter was designed to allow a bi-directional power flow by absorbing or injecting power according to the user selection. This power electronic-based inverter is capable of inverting the DC source from the battery to AC output or converting the excess generated AC power into DC for storage purposes. The bi-directional inverter is also capable of acting as the grid because it can provide voltage and frequency regulation during islanded operation. Furthermore, this compact bi-directional inverter was embedded with several important features including droop control, frequency shift power control and battery management system which are discussed in more detail in chapter 4. Figure 3.5 illustrates the bi-directional inverter with batteries installed at the experimental network. Each bi-directional inverter was connected to a battery bank.

Figure 3.5 Three units of bi-directional inverter integrated with batteries

The battery bank was made up of 16 Hoppeckke batteries which are deep cycle Absorbent Glass Mat (AGM) Valve Regulated Lead Acid (VRLA) types. Figure 3.6 shows the battery bank configuration of the bi-directional inverter. There were four battery strings. Each string consists of four batteries to provide 115 Ah capacity and 48 V for the bi-directional inverter. The four battery strings were connected in parallel to provide 460 Ah. This AGM type lead acid battery is a maintenance free operation, having a better lifecycle and longer charging cycle as compared to that of the water-type flooded batteries. Table 3.1 shows some of the technical details of the VRLA battery for the bi-directional inverter on laboratory experimental setup.

Table 3.1 Specification of the Hoppecke Solar. Bloc VRLA battery

	Specification
Capacity	115 (Ah)
DC Voltage	12 (V)
Type	AGM
Weight	46.0 (Kg)
Dimension	344 x 170 x 275 (mm)

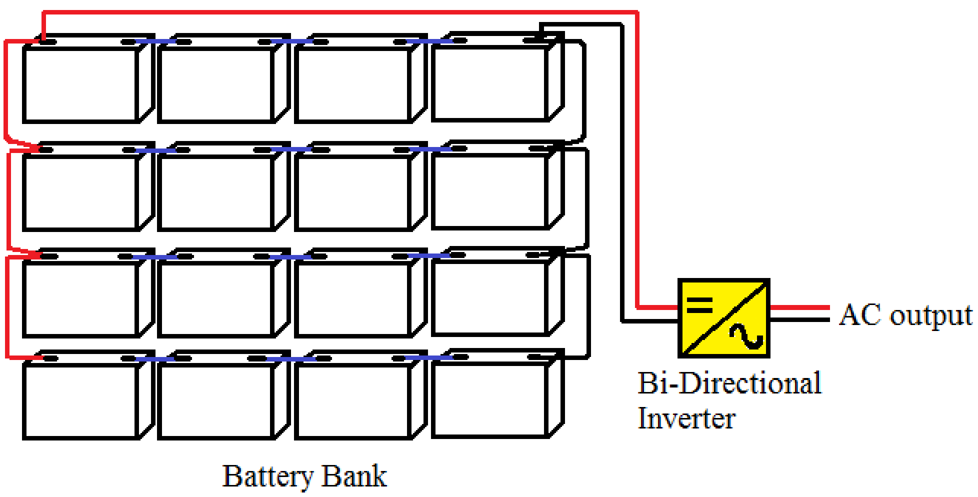


Figure 3.6 Battery bank configuration of the bi-directional inverter

3.6 Data Acquisition System

A data acquisition system is required to obtain the measured values of voltage and current from the PV systems and the load demands from the experimental low-voltage distribution network. The voltages and currents from the four different measurement points of the experimental network were recorded using National Instrument's analogue to digital voltage modules (NI 9225) and a current module (NI 9227) respectively. The voltage readings were taken by directly tapping the analogue input of the NI 9225 to the live and neutral wires of the respective measuring point. A ring type current transformer with the ratio of 250/ 5A was used to obtain alternating current reading at the measurement point. Thus, the measured current is required to be multiplied with a coefficient of 50 to offset the mismatch when evaluating the real and reactive power. Figure 3.7 shows the setup for obtaining the voltage and current measurement from the PV system with the aid of voltage and current modules.

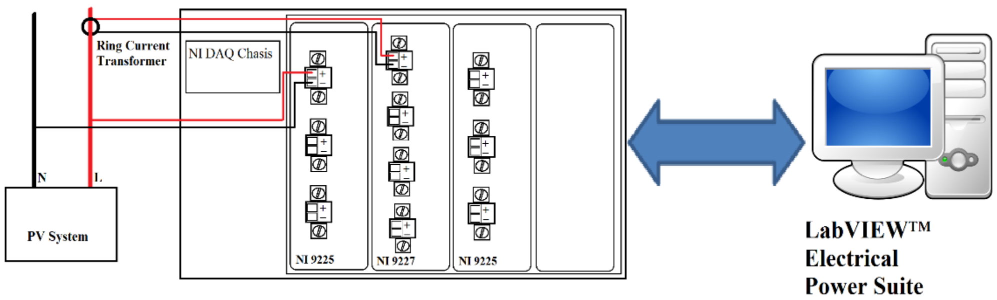


Figure 3.7 Setup for obtaining the voltage and current measurement from the PV system with the aid of voltage and current modules

Due to the high implementation cost of measuring every point of the experimental distribution network, the monitoring system was designed to obtain values from the output terminal of PV systems, load, grid and bi-directional inverters of the network. Figure 3.8 depicts the selected measurement points of the low-voltage experimental network. The electrical parameters including frequency, real power and reactive power at the selected measuring points were analysed and compiled by the supervisory computer with LabVIEW™ Electrical Power Suite 2013 was installed. The readings from the experiment were recorded at a time interval of 200 ms which is equivalent to one cycle of a 50 Hz electrical system and then stored into a spreadsheet via the LabVIEW™ programme. Figure 3.9 shows the configuration of the data acquisition system at the four selected points: load emulator, grid emulator, PV system and bi-directional inverter.

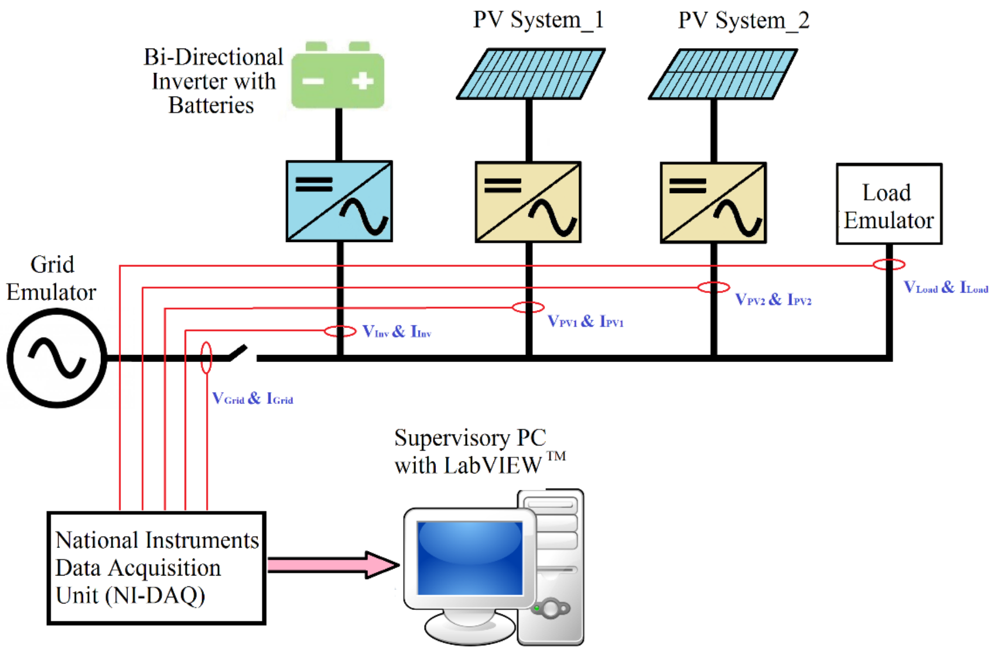


Figure 3.8 Measurement points of the low-voltage experimental network

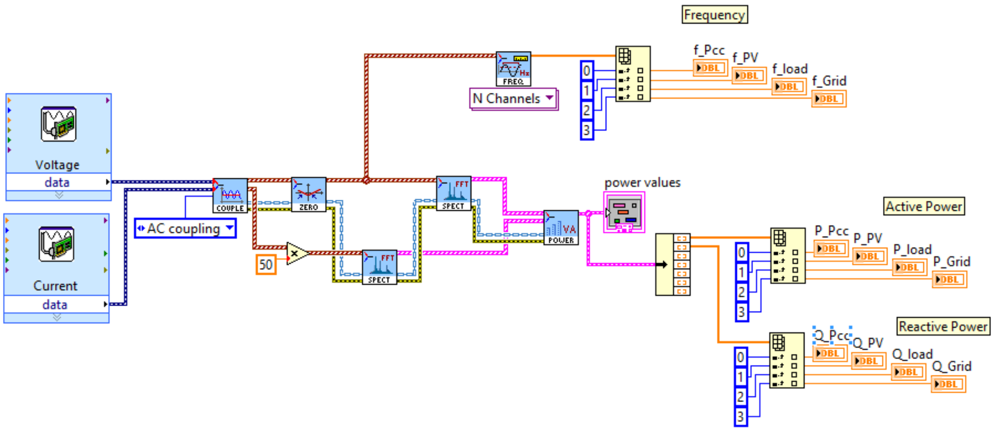


Figure 3.9 Configuration for the data acquisition system

3.7 Summary

An experimental low voltage distribution network was formed using a grid emulator to comply with the Malaysian distribution network standards. A 15 kVA synchronous generator, a load emulator, two commercial PV systems and a bi-directional inverter with batteries were installed on the experimental network. The TT earthing configuration of the low voltage distribution network by grounding at the transformer neutral point was used as it complies with the Malaysian distribution network configuration. A data acquisition system with LabVIEW™ was used to monitor and record the measurements at the selected points. The measurements obtained are current, voltage, frequency, real power and reactive power. Furthermore, the effect of the islanded operation of PV systems can be further studied by using the experimental distribution network through a few case studies.

CHAPTER 4

OPERATIONAL PRINCIPLE OF THE BI-DIRECTIONAL INVERTER

4.1 Introduction

The increased penetration of renewable energy onto the low voltage distribution network has changed the power flow from unidirectional to bi-directional. An adequate voltage and frequency control system is required to ensure the stability of operation of the entire network. As the voltage and frequency in a power system are mainly interrelated to the power balance between the generation and demand. Droop control method is widely applicable in most of the power electronic-based devices to allow voltage and frequency regulation on the electrical network. Hence, a bi-directional inverter integrated with batteries is proposed to provide a solution for voltage and frequency regulation on the islanded network. Once the distribution network is isolated from the grid, the droop-controlled bi-directional inverter takes charge as a grid forming unit to provide voltage and frequency regulation on the islanded network without any external communication devices. In this chapter, the details and operational principle of the proposed bi-directional inverter are presented. A preliminary case study is designed to investigate the islanded operation with PV systems.

4.2 Droop Control of the Bi-Directional Inverter

In the conventional electrical system, a frequency droop is implemented through the measurement of the system's frequency after the power outputs are adjusted. However, the Selfsync™ control measures the output power of the bi-directional inverter and alters its output frequency accordingly. The bi-directional inverter utilises a control algorithm, namely Selfsync™ to allow a slight change in voltage and frequency in order to obtain a variation in the real and reactive power output of the bi-directional inverter. The bi-directional inverter is coupled with a small inductor to allow the conventional droop to be applicable in the low voltage distribution network. This unique control algorithm programmed on the bi-directional inverter allows voltage and frequency changes in accordance with the measured real and reactive power changes (Engler, 2004).

Figure 4.1 shows the block diagram of the Selfsync™ control algorithm which is divided into four sections, namely power acquisition, decoupling, droop control and voltage reference. Figure 4.1(a) illustrates the power acquisition that obtains the instantaneous voltage and current from the measurement point to compute the real and reactive power of the network. The power acquisition block consists of a customised filter design with several proportional and integrating elements that are used to create a phase displaced by 90 degrees relative to the first periodic signal. Thus, the real power and reactive power in steady-state operation can be determined from the voltage and current inputs respectively.

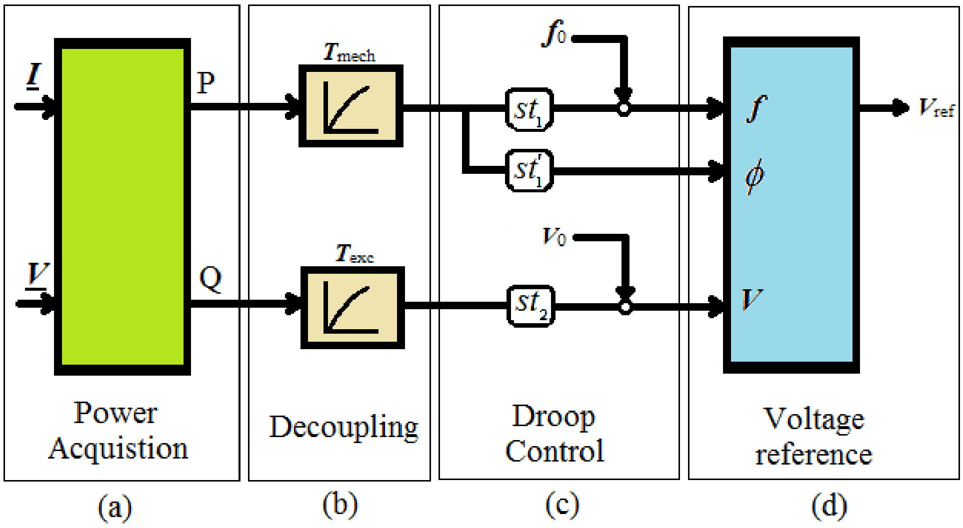


Figure 4.1 Overview of the Selfsync™ control algorithm

Figure 4.1(b) shows that the real and reactive power from the power acquisition block are fed to the decoupling stage in order to decouple the real and reactive power control during current changes which are more than one network period (Engler, 2004). The first order time lags of the moment of inertia, T_{mech} is to emulate the synchronous generator time delay behaviour. The T_{mech} and the excitation time constant, T_{exc} decouple the active and reactive power, respectively to provide further smoothing effect. The measured power is used for voltage and frequency regulation with droop controls. Figure 4.1(c) shows that the decoupled active power, P is multiplied with a droop coefficient, st_1 and added to the reference frequency, f_0, to determine the instantaneous frequency, f whereas the reactive power, Q is multiplied with a droop coefficient, st_2 and added with the reference voltage, V_0 to determine the magnitude voltage, |V|. Therefore, the reference voltage, V_{ref} of the bi-directional inverter can be expressed as follows:

$$V_{ref} = |V| \sin(2 \bullet \pi \bullet f \bullet t) \tag{4.1}$$

The frequency droop enables a frequency change of 1%, while the voltage droop allows a voltage change of 4 % of the nominal value (Engler, 2005). When the real power in the network increases, the frequency decreases from the reference frequency, f_0. Vice versa, when the frequency deviates from this reference frequency, the droop control increases the frequency and restore the frequency back to the reference value of 50 Hz. Similarly, when the bi-directional inverter detects a change in voltage, the voltage droop varies the reactive power to reinstate to the reference voltage, V_0. Figure 4.2 depicts the droop control for the frequency and voltage of the bi-directional inverter as a function of real and reactive power respectively.

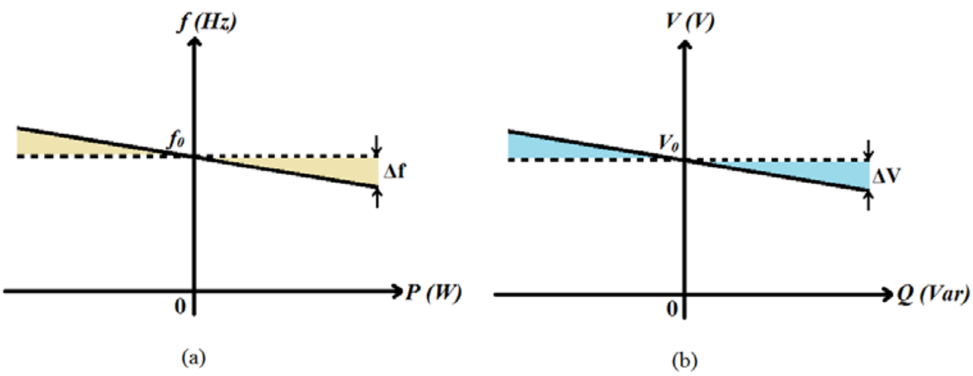


Figure 4.2 (a) Real power and frequency (P-f) Droop and (b) Reactive power and voltage (Q-V) Droop

The phase correction droop, st_1’ is introduced to maintain the stability of the system when a large deviation occurs in the phase angle. The reference voltage, V_{ref} which is the output voltage can be written as follows:

$$V_{ref} = |V| \sin\left[(2 \bullet \pi \bullet f \bullet t) + \phi\right] \tag{4.2}$$

The reference voltage, V_{ref} is then passed on to the pulse width control circuit to be compared with the actual voltage. Thus, this instantaneous value allows rapid changes in the inverter and avoids the circulating currents among the inverters. When two voltage source inverters are connected in parallel, a small difference between voltage and phase angle can cause the real and reactive power to flow between the two inverters (Engler, 2004). The bi-directional inverter with Selfsync^{TM} has the ability to enable the parallel operation with other inverters without the needs of any external communication devices.

4.3 Frequency Shift Power Control

Frequency Shift Power Control (FSPC) is an operating mechanism adopted by the proposed bi-directional inverter to prevent overcharging the fully charged batteries when there is excess power generated by renewable energy sources in the network. The FSPC detects this circumstance and adjusts the frequency at the output of the bi-directional inverter, so as to limit the power generated from the renewable energy sources such as the wind and solar energy. Figure 4.3 shows the overview of the FSPC. If the system frequency is less than or equivalent to the reference frequency, f_0 of 50 Hz, the bi-directional inverter absorbs the maximum available power from the renewable energy sources. On the other hand, when the system frequency increases above the set-point $F_{AC\text{-}Start}$, the bi-directional inverter starts to limit the power output of the PV system and prevents it from overcharging of the batteries. Furthermore, if the frequency keeps increasing until $F_{AC\text{-}Stop}$, as shown in Figure 4.3, the PV system is tripped off to prevent battery overcharging and hence avoid further increase in the frequency that might collapse the network operation. One of the advantages of FSPC is that no additional communication devices are used to monitor the power balance between the demand and generation.

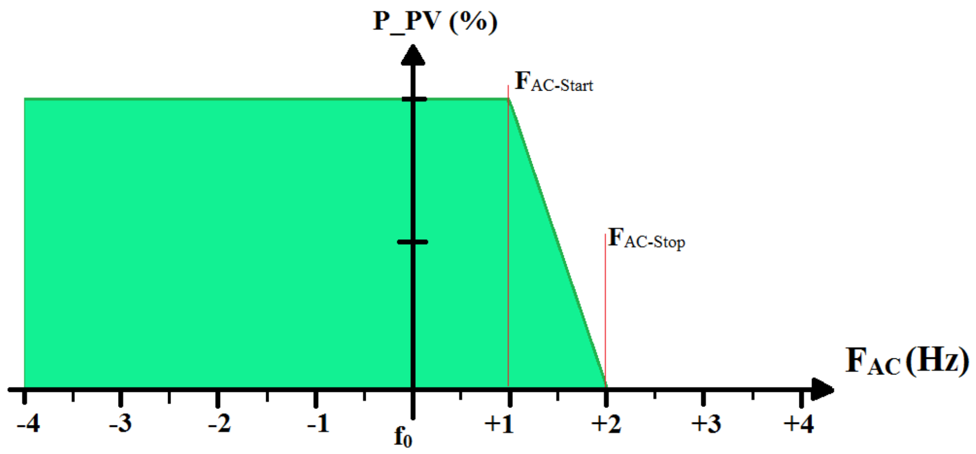


Figure 4.3 Frequency Shift Power Control

4.4 Battery Management System

A battery management system can be easily found in power electronic-based devices interconnected with batteries where it is used to monitor the battery's state of charge (SOC) level, so as to optimise the battery lifespan. The SOC can be defined as the amount of charge available in the battery. By using the measuring voltage and current to create the current-voltage models for SOC calculation can be provided rather than that obtained by only measuring from the voltage (SMA, 2010). The battery management system of the bi-directional inverter consists of three charging phases to provide effective control in the battery. These phases are known as bulk phase, absorption phase and float phases (SMA, 2010). During the bulk phase, the battery will be charged at a constant rate until the SOC level reaches 80%. After that, the system will change to absorption phase, where the system switches to a constant voltage charging mode by maintaining the voltage per cell while decreasing the current flow to the battery. The charging mode switches to the float phase to keep the battery in a fully charged state without overcharging. At float phase, the current flow to the batteries is very small, nearly zero. In the case of battery charging with SOC greater than the upper threshold of 90%, the operating mechanism of FSPC, as discussed in section 4.3 will also take part to protect the batteries from overcharging. However, if the battery SOC level drops below the lower threshold of 40%, the bi-directional inverter will immediately trip off in order to protect the batteries from deep discharging that potentially reduces the battery life span.

4.5 Summary

A bi-directional inverter integrated with batteries is introduced on the distribution network to allow the islanded operation of PV systems. The bi-directional inverter which uses the Selfsync™ control algorithm will automatically synchronise with the grid without any additional devices to allow for a parallel operation with the utility grid during grid-connected operation. Furthermore, the droop-controlled bi-directional inverter plays an important role during the islanded operation with PV systems due to the capability of regulating the voltage and frequency and provides an adequate control in the power flow of the network. In addition, the operational mechanism of the bi-directional inverter namely frequency power shift control and the battery management system are exploited for battery protection. Nevertheless, the bi-directional inverter with batteries not only allows the PV system to operate in grid-connected mode, but also during islanded operation. Thus, the droop-controlled bi-directional inverter is proposed to conduct the islanded operation of PV systems on the distribution network which is discussed in chapter 5.

CHAPTER 5

VOLTAGE AND FREQUENCY CHANGES DURING THE ISLANDED OPERATION OF PV SYSTEMS

5.1 Introduction

In any electrical network, the electrical parameter including voltage and frequency must be well controlled. An adequate voltage and frequency control technique of the distribution network can ensure the stability of the entire electrical network. If the voltage and frequency of the islanded network are not maintained within the statutory limit, the household devices are likely to be damaged. Rotary based machines such as synchronous generators can be used to compensate for the steady state power mismatches. However, the response time is limited due to the inertia and the time delay is inevitable in rotating machines. Alternatively, the energy storage system is selected to provide a fast response in mitigating the power mismatches during the transition period. Due to safety concerns, islanded operation with renewable energy sources is not allowed under the existing international framework as stated earlier in section 2.5. Any renewable energy source installed in the islanded network is required to shut down after the isolation. The following section 5.2 illustrates the preliminary study on the islanded operation with PV systems. The experimental result has illustrated that the islanded operation with PV system is unlikely to happen due to the anti-islanding protection system in the PV inverter. Therefore, droop-controlled bi-directional inverters are proposed to be used so that the voltage and frequency of the distribution network are well-regulated when the grid is out of service. This chapter presents the findings on the droop controlled bi-directional inverters to reduce the power mismatches so that the voltage and frequency of the islanded network can stay within the statutory limit during islanded operation. Several case studies are designed to investigate the feasibility of the proposed idea in conducting the islanded operation of PV systems with the appropriate control mechanism.

5.2 Initial Experimental Study on Conducting the Islanded Operation of PV Systems

The anti-islanding protection system is integrated into almost every PV inverter to disconnect the inverter once islanded operation is detected. The passive islanding detection methods form the most fundamental anti-islanding protection system in modern power electronic based inverter. The PV inverter detects the occurrence of islanding event based on the voltage and frequency deviation of the islanded network. Once the changes in the voltage and frequency exceed NDZ, then the islanding detection methods will immediately trigger the protection relay to disconnect the PV inverter. Figure 5.1 shows the typical connection of a PV system with a load to the utility grid.

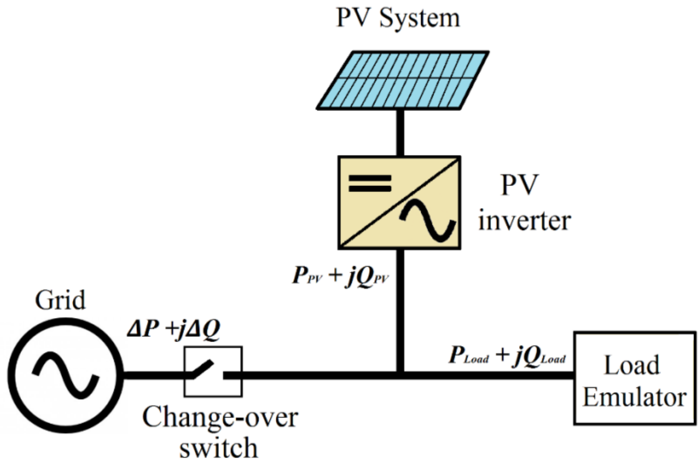


Figure 5.1 Network configuration for conducting the islanded operation of PV system

The voltage and frequency fluctuation greatly depends on the power mismatches of the islanded network as the following equations:

$$\Delta P = P_{Load} - P_{PV} \tag{5.1}$$

$$\Delta Q = Q_{Load} - Q_{PV} \tag{5.2}$$

where P_{Load} and Q_{Load} represent the real and reactive power of the load emulator P_{PV} and Q_{PV} are the real and reactive power generated from the PV system respectively.

Figure 5.2 illustrates the non-detection zone (NDZ) of the PV inverter with specified over- and under- frequencies and over- and under- voltages. Referring to the Malaysian Standards MS IEC 60038; 2006, the steady state voltage during normal operation should be maintained within + 10% and – 6% at all times, while the frequency of the network need to be kept at ±1 % of the nominal frequency.

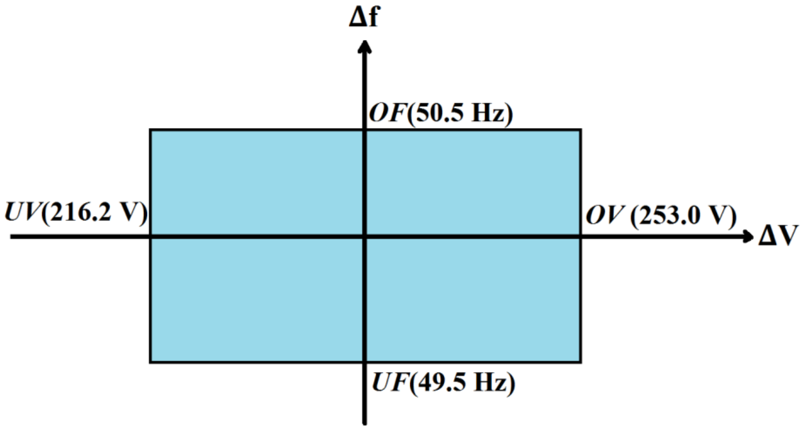


Figure 5.2 NDZ of the PV system

The intermittent power generation from the PV systems can create ΔP and ΔQ after being isolated from the grid. If the power mismatches are small enough, then the frequency and voltage of the islanded network is possible to stay within NDZ. However, this circumstance is unlikely to happen.

In this stage, the study of the voltage and frequency changes from a grid-connected operation to the islanded operation of PV systems is conducted. Figure 5.3 depicts the experimental setup for this case study. A 15 kVA synchronous generator was used to emulate the utility distribution network. The PV system and a controllable load emulator were connected to the grid emulator. This case study began with a 500 W load connected to the experimental network while the power generated by the PV system was 600 W. The load power was selected to be as close to the PV power generated so that the power mismatches can be minimised.

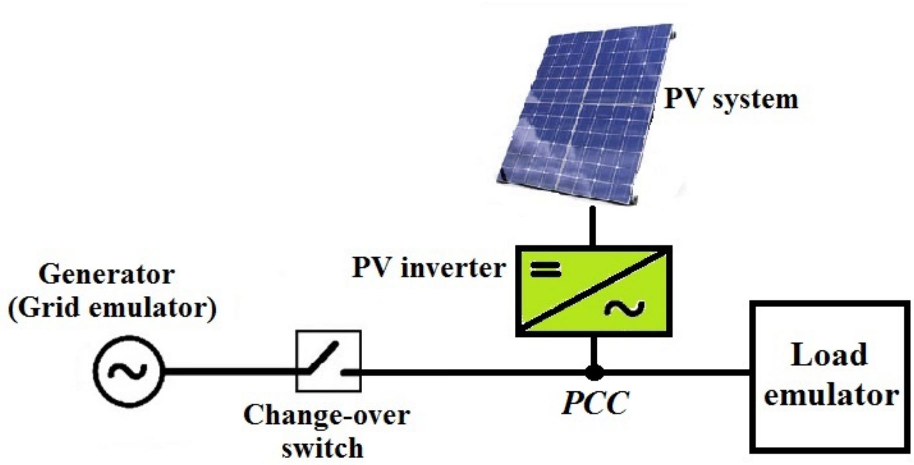


Figure 5.3 Network topology for the islanded operation of PV system

Figure 5.4 and Figure 5.5 show the voltage and frequency changes of the islanded network respectively. It was observed that the network is isolated at time, t = 30s. After the network is islanded, the voltage and frequency have dropped from the nominal voltage of 240 V and 50 Hz to nearly 0 V throughout the islanded operation. The experimental result shows that the voltage and frequency of the distribution network clearly exceed the NDZ. Hence, the anti-islanding protection system triggers the inverter and forces the PV inverter to disconnect. Therefore, the experimental results have shown that the islanded operation with PV system is unlikely to happen due to the presence of anti-islanding protection system within the inverter.

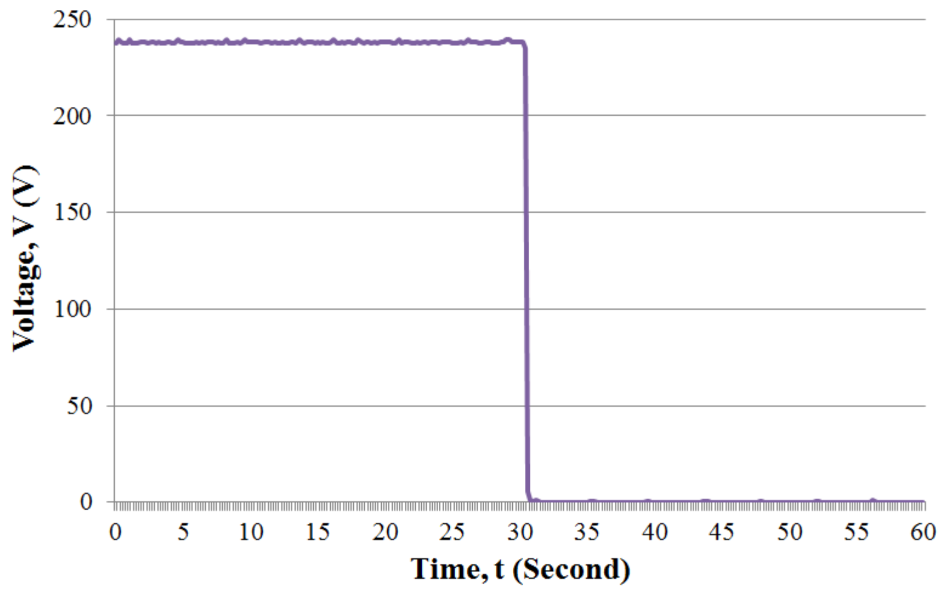


Figure 5.4 Voltage of the distribution network during the islanded operation of PV system

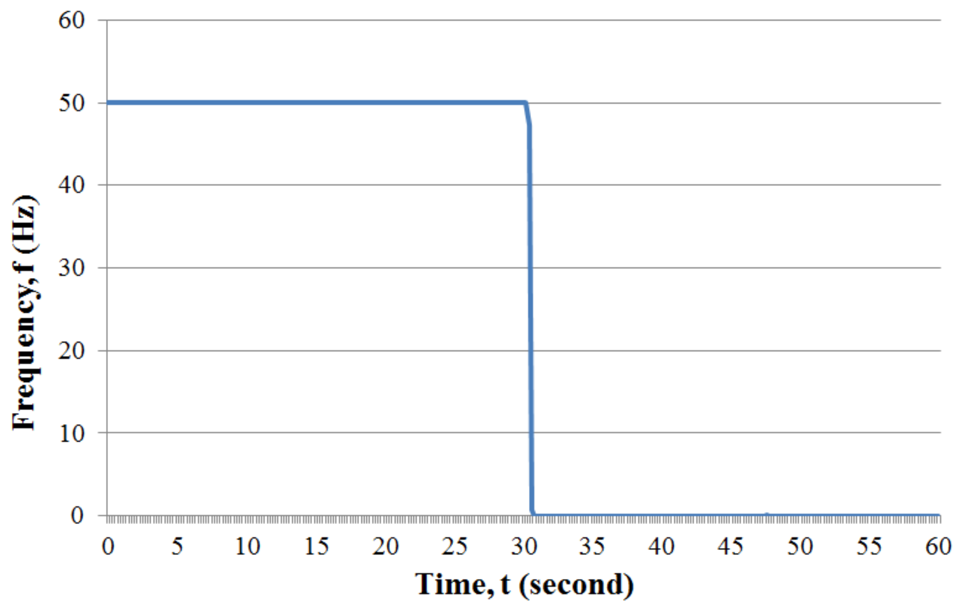


Figure 5.5 Frequency of the distribution network during the islanded operation of PV system

5.3 Islanded Operation of PV Systems with the Use of Bi-Directional Inverter

The bi-directional inverter integrated with batteries can be implemented into the network to allow the islanded operation of PV systems as illustrated in Figure 5.6. A droop controlled bi-directional inverter can be used to minimise the mismatches of ΔP and ΔQ so that the voltage and frequency of the islanded network can be operated without exceeding the statutory limits. Thus, when the bi-directional inverter is introduced into the experimental network, the equation 5.1 and 5.2 can be modified as follows:

$$P_{Grid} = P_{Load} - P_{PV} + P_{Inv} = \Delta P + P_{Inv} \tag{5.3}$$

$$Q_{Grid} = Q_{Load} - Q_{PV} + Q_{Inv} = \Delta Q + Q_{Inv} \tag{5.4}$$

where P_{Inv} and Q_{Inv} are the pre-islanded real and reactive power of the inverter.

Once the grid is isolated, the bi-directional inverter will be transformed to act as the utility grid. The real and reactive power of the droop-controlled inverter will alter from the pre-islanded values, $P_{Inv} + jQ_{Inv}$, to the values that are same as the power mismatches, $\Delta P + j\Delta Q$, of the islanded network. Hence, the total changes in the real and reactive power output of the inverter are described below.

$$\Delta P_{inv} = \Delta P + P_{inv} \tag{5.5}$$

$$\Delta Q_{inv} = \Delta Q + Q_{inv} \tag{5.6}$$

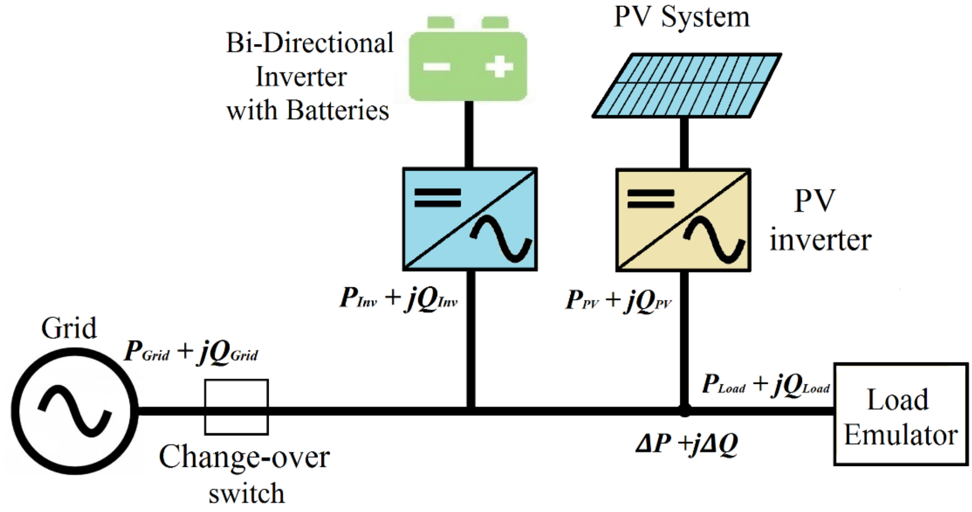


Figure 5.6 Illustration of PV system and load with the grid integrated with the bi-directional inverter during grid-connected operation

The bi-directional inverter is equipped with droop mechanisms: real power-frequency droop (P-f droop) and reactive power- voltage droop (Q-V droop). The frequency change, Δf and voltage change, ΔV are dependent on the ΔP_{Inv} and ΔQ_{Inv}, respectively. The equations below show the frequency and voltage deviations, Δf and ΔV at the inception of the islanded operation.

$$\Delta f = K_f \times \Delta P_{Inv} \tag{5.7}$$

$$\Delta V = K_V \times \Delta Q_{Inv} \tag{5.8}$$

where K_f and K_V are the frequency and voltage changes coefficients respectively

After the frequency and voltage of the islanded network are stabilised, the droop-controlled bi-directional inverter will provide the real and reactive power, P_{Inv}^* and Q_{Inv}^* to be the same as ΔP and ΔQ as depicted in Figure 5.7. Thus, the following equations are applicable during the islanded operation of PV systems.

$$P_{Inv}^{*} = \Delta P \quad (5.9)$$

$$Q_{Inv}^{*} = \Delta Q \quad (5.10)$$

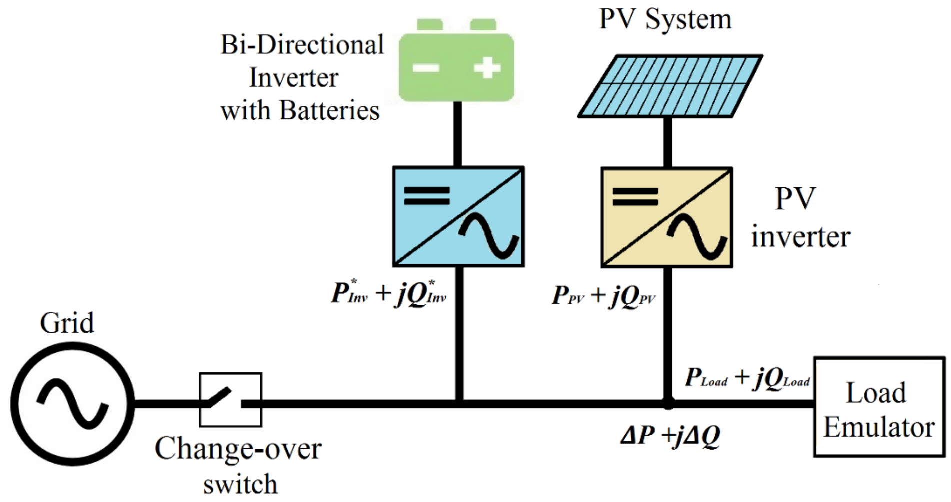


Figure 5.7 Illustration of PV system and load with the integration of bi-directional inverter during islanded operation

5.4 Experimental Study on Conducting Islanded Operation of PV Systems with the Use of Bi-directional Inverter

In this case study, the droop-controlled bi-directional inverter integrated with batteries was inserted into the experimental low voltage distribution network. Figure 5.8 shows the experimental setup that was used to investigate the voltage and frequency changes during the islanded operation of PV systems.

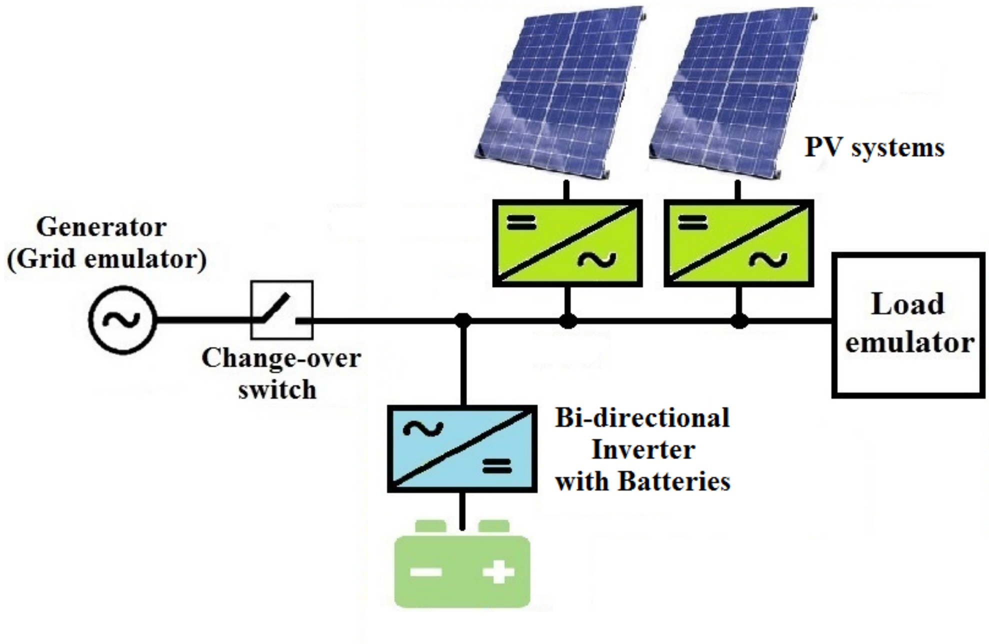


Figure 5.8 Network topology for the islanded operation of PV systems with the use of the bi-directional inverter

During the grid-connected operation, the bi-directional inverter allows power to flow from the grid to charge the batteries in order to maintain the SOC level. In most of the battery applications, the charging current is pre-set to be 10% of the battery capacity. From the battery specification provided by the manufacturer, the allowable charging current for batteries is from 5 A to 20 A over 100 Ah rating. Therefore, maximum charging current of the bi-directional inverter is selected at 50 A for 450 Ah batteries capacity which is in accordance with the specification sheet (Hoppecke Batterian Gmbh & Co. KG, 2009). The bi-directional inverter allows a maximum allowable charging current to flow into the batteries and charges to 2500 W when the grid is present. This selection is to optimise the generator run-time by obtaining a more economic operation with a reduction in greenhouse gas emission. The bi-directional inverter with unique control system is able to act as the grid to provide voltage and frequency reference for the PV inverter while maintaining voltage and frequency of the islanded network within the statutory limits during islanded operation. Hence, three scenarios have been carried out in section 5.4.1 to 5.4.3 using the experimental low voltage distribution network.

5.4.1 Scenario 1: The Bi-Directional Inverter's Real Power Difference, ΔP_{inv} is Between 0 W and 2500 W

This scenario was considered to investigate the voltage and frequency changes of the islanded network integrated with the bi-directional inverter when its real power mismatch, ΔP lies between -2000 W to 0 W. The power output from the PV system was 1200 W while the load was 500 W, thus creating a power mismatch, ΔP of -700 W.

Figure 5.9 shows the real power variation of the bi-directional inverter, P_{inv}. From 0 to 90 seconds, the experimental network was operated in grid-connected mode, hence the bi-directional inverter was charging at 2530 W. At 90 seconds, the experimental network with PV system was disconnected from the grid causing the real power output of the bi-directional inverter, P_{inv}* to be -700 W. This creates a total real power change, ΔP_{inv} of 1830 W at the inception of islanding. A negative value of the bi-directional inverter real power indicates power flow of the bi-directional inverter is in the charging mode while a positive value represents the bi-directional inverter in the discharging mode. Figure 5.10 shows the reactive power variation of the bi-directional inverter, Q_{inv}. At 90 seconds, the experimental network with PV system was disconnected from the grid and experiences a total change of reactive power, ΔQ_{inv} of -340 Var after isolation as shown in Figure 5.10.

Figure 5.11 and Figure 5.12 show the frequency and voltage of the experimental low voltage distribution network during islanded operation respectively. Figure 5.11 and Figure 5.12 illustrate that the islanded network experienced a voltage and frequency changes of 12.80 V and 0.55 Hz, respectively immediately after the isolation. Once the voltage and frequency of the network were stabilised, the bi-directional inverter absorbed the excess power P_{inv}* and Q_{inv}*of 750 W and 80 Var into the batteries while maintaining the voltage and frequency of the islanded network at 241 V and 50 Hz, respectively.

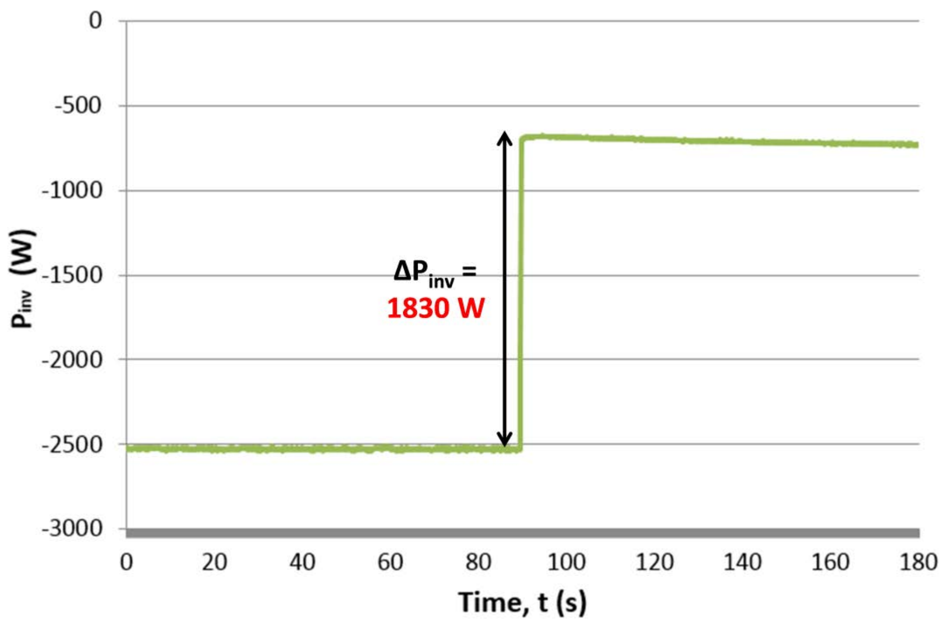


Figure 5.9 Real power, P_{inv} of the bi-directional inverter during transition from grid-connected operation to islanded operation

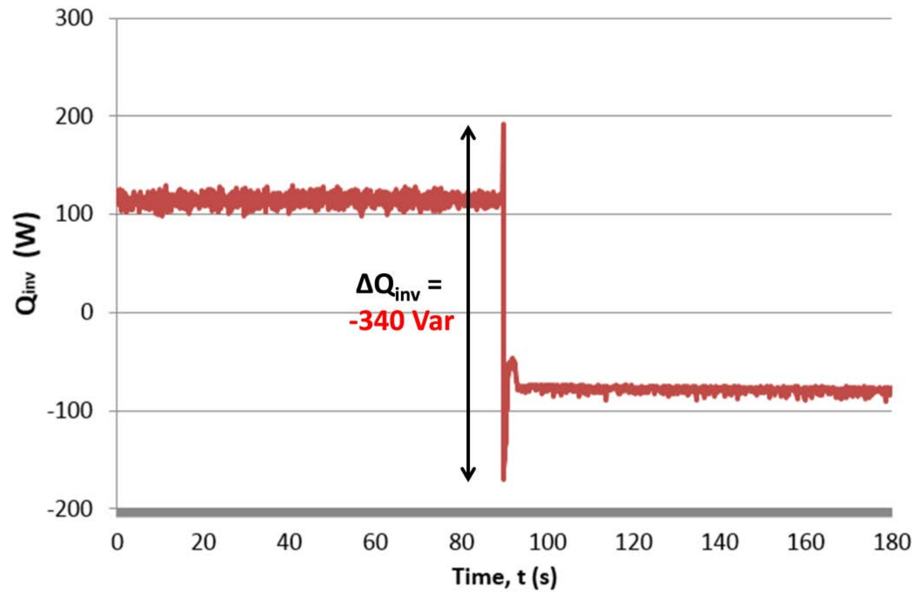


Figure 5.10 Reactive power, Q_{inv} of the bi-directional inverter during the transition from grid-connected operation to islanded operation

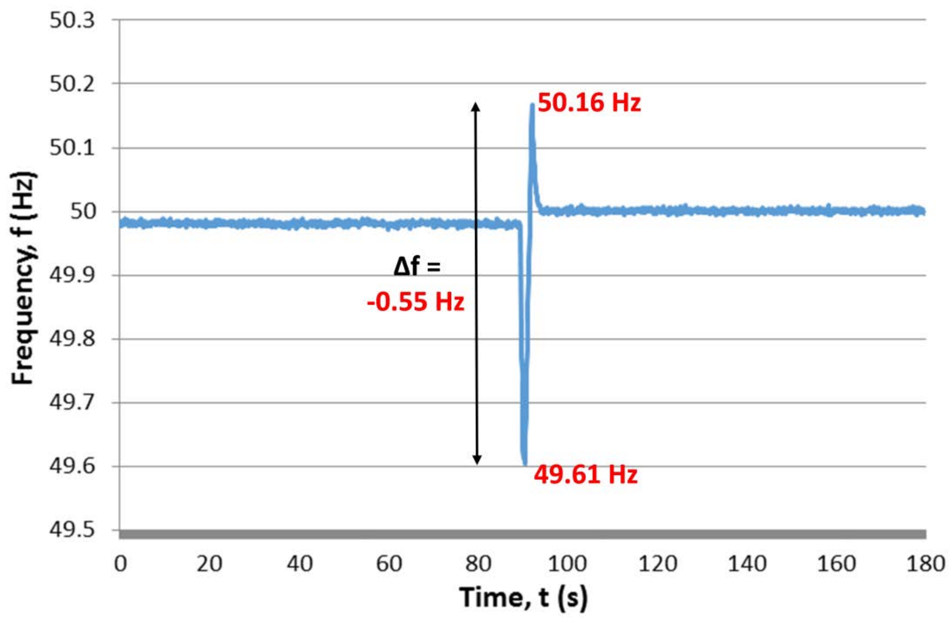


Figure 5.11 Frequency of the experimental low voltage distribution network of Scenario 1

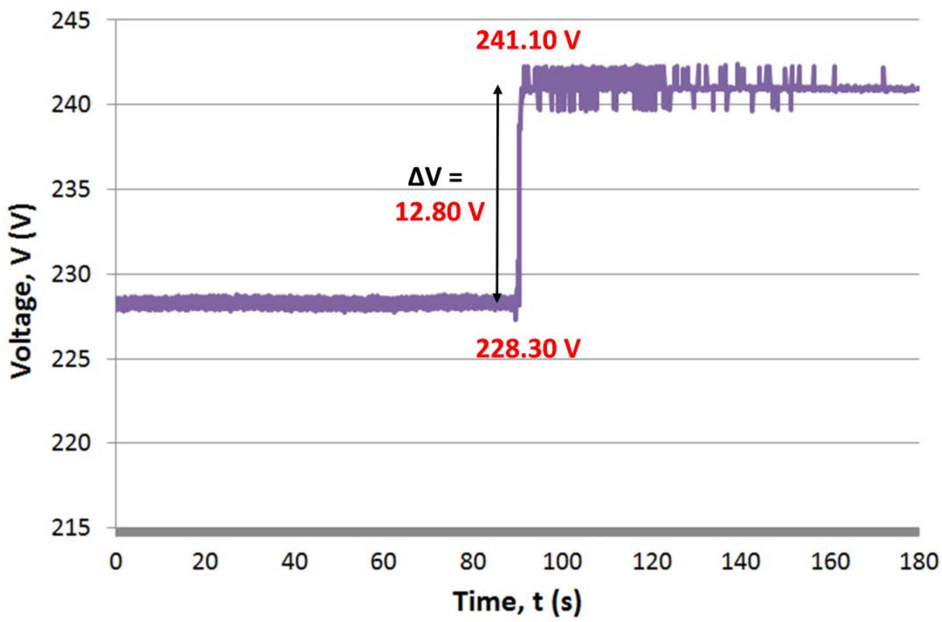


Figure 5.12 Voltage of the experimental low voltage distribution network in Scenario 1

5.4.2 Scenario 2: The Bi-Directional Inverter's Real Power Difference, ΔP_{inv} is Greater Than 2500 W

This scenario was to study the islanded network's voltage and frequency changes when the power mismatches, ΔP is greater than 0 W. This scenario considered a peak load condition of the distribution network and a low solar power generation due to poor weather condition. The PV power output from the PV system was 550 W and the load was set at 1300 W, thus resulting in a power mismatches, ΔP of 650 W.

Figure 5.13 shows the real power changes of the bi-directional inverter, P_{inv} while Figure 5.14 shows the reactive power changes of the bi-directional inverter, Q_{inv}. The experimental network operated in grid-connected operation from 0 to 90 seconds. At t = 90 seconds, the experimental network was isolated from the grid and created a total real and reactive power changes of the bi-directional inverter, ΔP_{inv} and ΔQ_{inv} of 3460 W and 450 Var, respectively at the inception of islanding as demonstrated in Figure 5.13 and Figure 5.14.

Figure 5.15 and Figure 5.16 show the frequency and voltage of the experimental low voltage distribution network for scenario 2. Figure 5.15 illustrates that the frequency of the islanded network dropped to 49.15 Hz, which is lower than the lower frequency threshold of 49.5 Hz as a result of large real power variations. Figure 5.16 shows that the voltage of the islanded network dropped to 215.15 V which exceeded the lower voltage threshold at the inception of islanding. The experimental results illustrated that the large deviation in real and reactive power has resulted in large changes in frequency and voltage according to the predefined droop control of the bi-directional inverter. Hence, this scenario indicates the limitation of the bi-directional inverter to maintain the frequency and voltage within the statutory limits when the ΔP_{inv} is greater than 2500W during the islanded operation with PV systems.

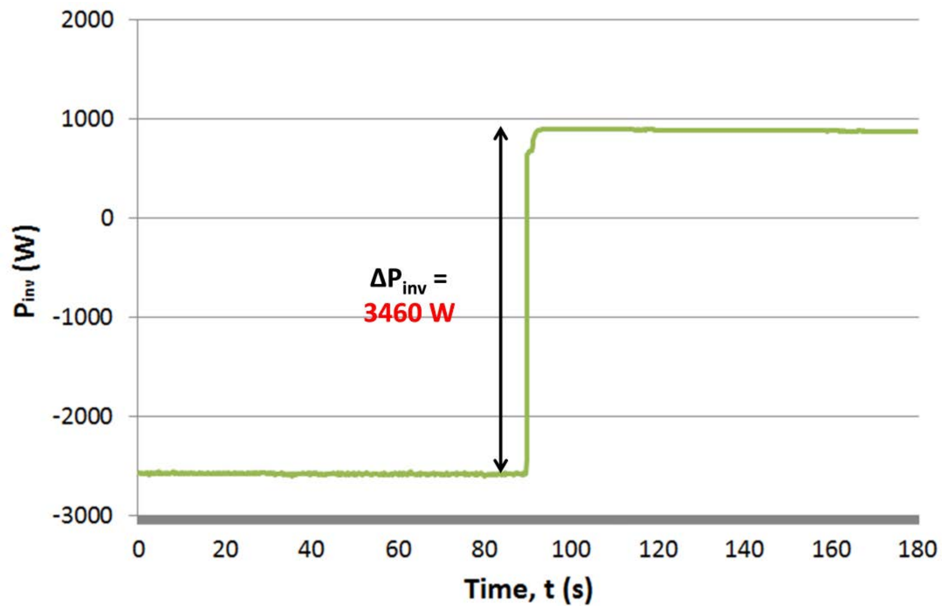


Figure 5.13 Active power, P_{inv} of the bi-directional inverter change during the transition from grid-connected operation to islanded operation

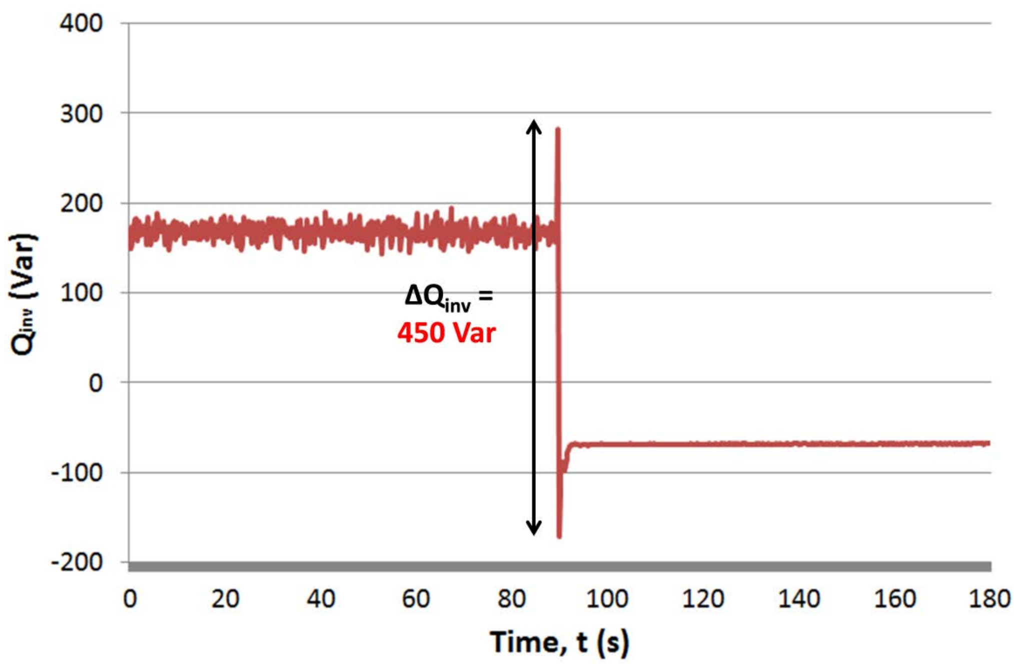


Figure 5.14 Reactive power, Q_{inv} of the bi-directional inverter change during the transition from grid-connected operation to islanded operation

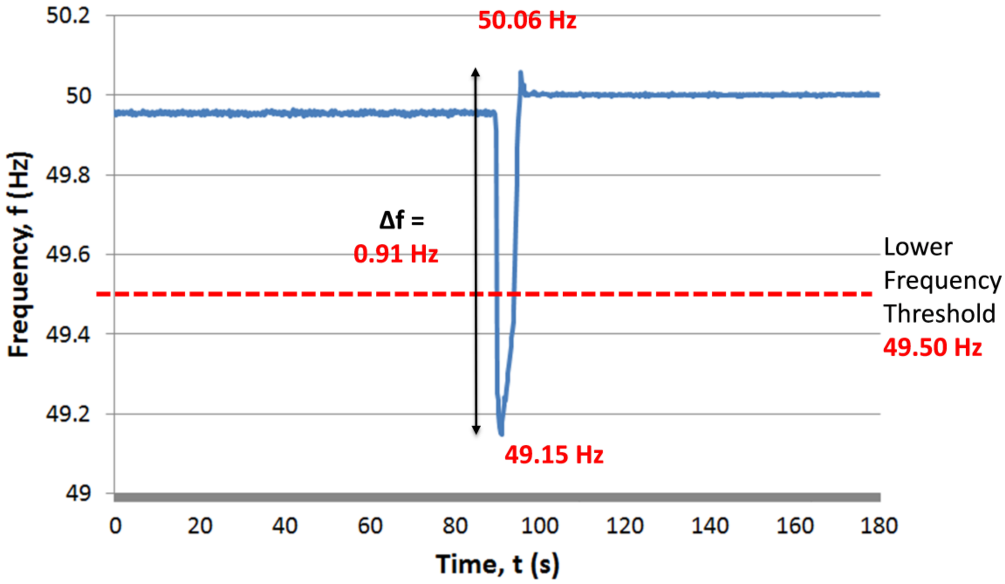


Figure 5.15 Frequency of the experimental low voltage distribution network of scenario 2

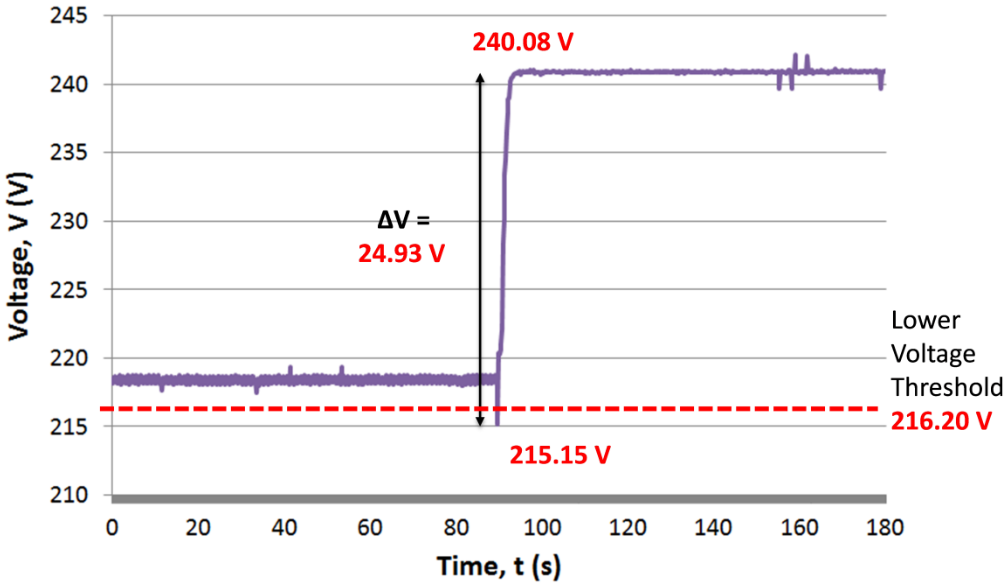


Figure 5.16 Voltage of the experimental low voltage distribution network in scenario 2

5.4.3 Scenario 3: The Bi-Directional inverter's Real Power Difference, ΔP_{inv} is Less Than 0 W

This scenario was carried out to study the performance of the bi-directional inverter while conducting the islanded operation of PV systems operated under sunny weather condition when the minimum load was connected. The controllable resistive load, P_{load} was set at 1000 W while the PV power output was 5200 W. Thus, the power mismatch, ΔP was recorded at -4200 W.

Figure 5.17 and Figure 5.18 show the real power variation of the bi-directional inverter, P_{inv} and reactive power variation of the bi-directional inverter, Q_{inv}. The experimental network operated in grid-connected operation from 0 to 90 seconds. At t = 90 seconds, the experimental network was isolated from the grid. Figure 5.17 and Figure 5.18 show the total changes of real and reactive power changes, ΔP_{inv} and ΔQ_{inv} of -1350 W and 420 Var, respectively at the inception of islanding.

Figure 5.19 shows the frequency of the experimental low-voltage distribution network for scenario 3. Figure 5.19 shows that the frequency of the islanded network exceeded the upper statutory limit of 50.5 Hz soon after the isolation and kept increasing until it hit the over-frequency threshold of the PV inverter that caused one of the PV system to be shut down. This scenario shows that the excess power generated from the two PV systems is too much for the bi-directional inverter to absorb at the default charging current of 50 A.

Therefore, the frequency shift power control algorithm embedded within the bi-directional inverter increased the islanded network frequency and subsequently cause the PV inverter to be disconnected. Figure 5.20 illustrates the voltage of the experimental low-voltage distribution network for scenario 3. Figure 5.20 shows that the islanded network voltage was reduced by 12.63 V after the isolation. According to the droop control, the increment in reactive power by the bi-directional inverter will result in a decrement of the islanded network voltage. Thus, the experimental results have presented another scenario where the bi-directional inverter was unable to keep the voltage and frequency of islanded network within the permissible range during islanded operation with PV systems.

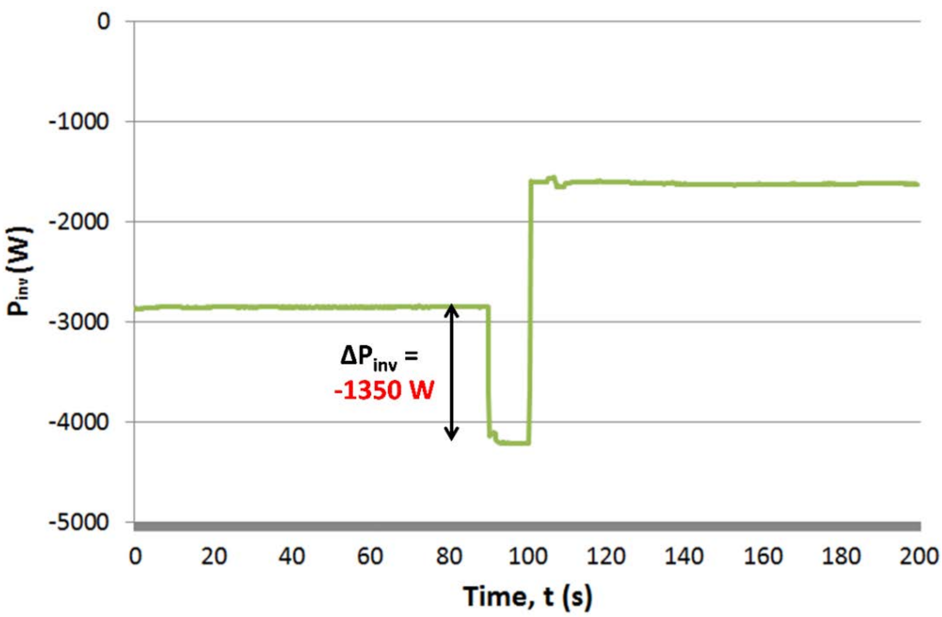


Figure 5.17 Active power, P_{inv} of the bi-directional inverter change during the transition from grid-connected operation to islanded operation

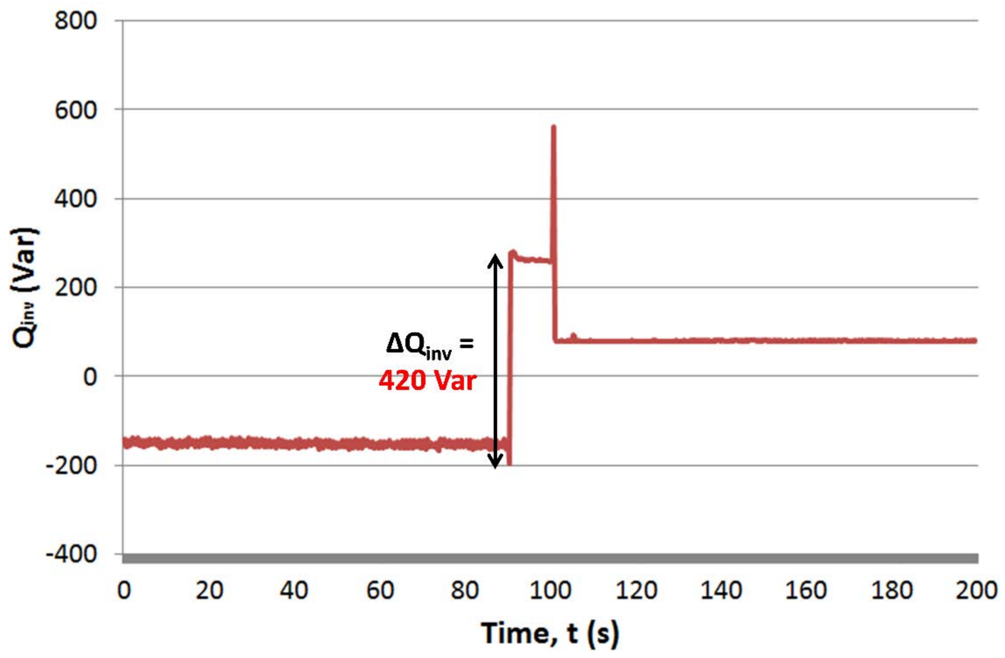


Figure 5.18 Reactive power, Q_{inv} of the bi-directional inverter change during the transition grid-connected operation to islanded operation

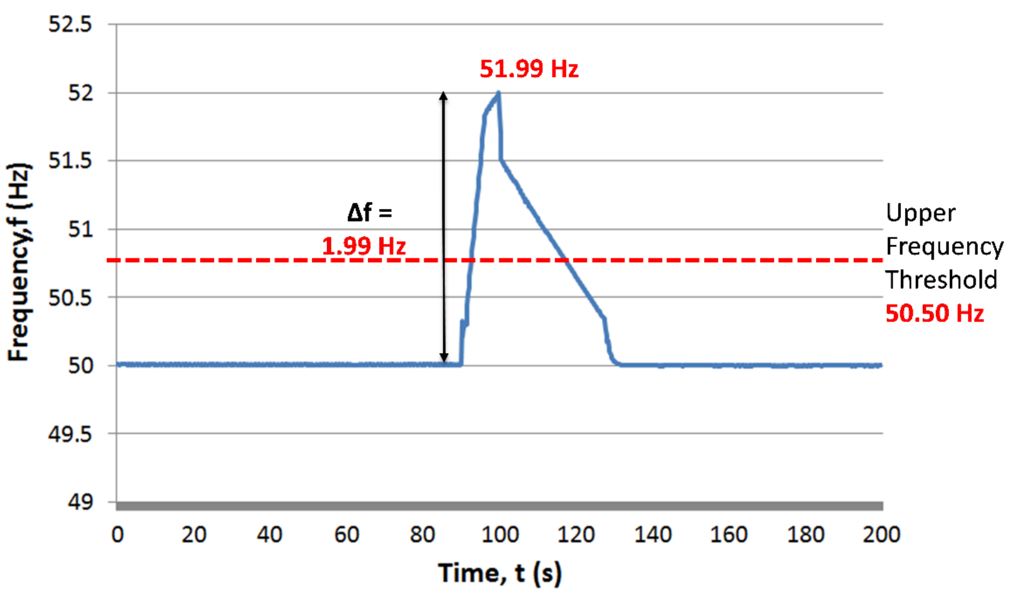


Figure 5.19 Frequency of the experimental low-voltage distribution network in Scenario 3

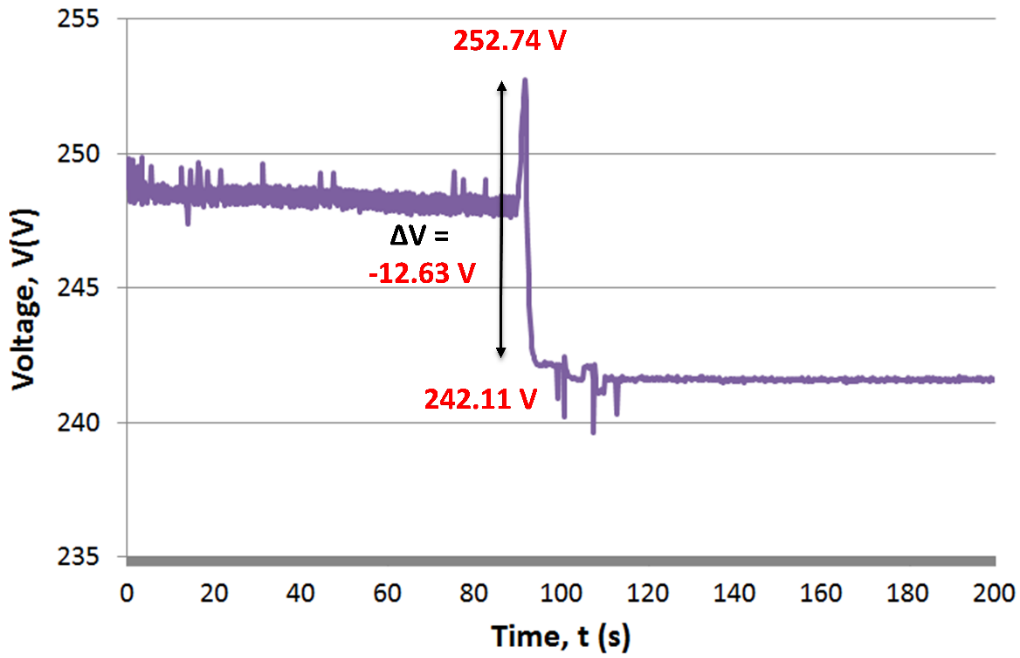


Figure 5.20 Voltage of the experimental low-voltage distribution network in Scenario 3

5.4.4 The Operational Boundary of the Bi-directional Inverter

The operational boundary of the bi-directional inverter was established to determine the ability of the inverter in maintaining the voltage and frequency within the statutory limits by manipulating P_{inv} and Q_{inv}. Figure 5.21 depicts the operational boundary of the bi-directional inverter obtained from the values of ΔP_{inv} and ΔQ_{inv} over several case studies. It is shown that the bi-directional inverter was capable of maintaining the frequency and voltage within statutory limits as long as ΔP_{inv} stayed within the range of 0 W to 2500 W and ΔQ_{inv} within the range of 0 to -480 Var. When ΔP_{inv} and ΔQ_{inv} are maintained within the operational boundary, the PV systems remained operational during the islanded operation without being disconnected by the anti-islanding protection system.

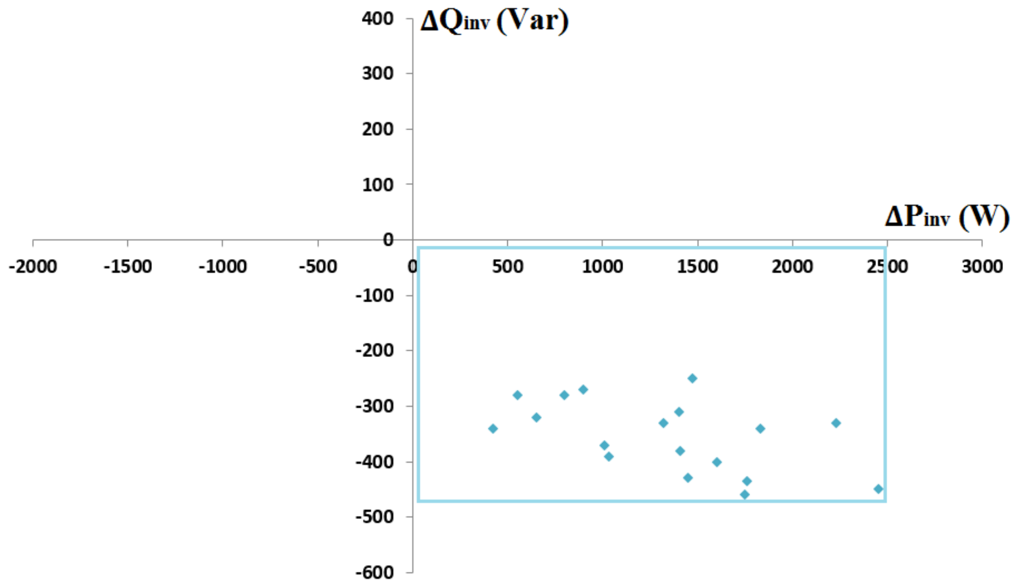


Figure 5.21 Operational boundary of the bi-directional inverter

5.5 The Developed Control Algorithm

This section describes the development of the control algorithm to keep the voltage and frequency of the distribution network during the islanded operation within the statutory limits. The bi-directional inverter can maintain the voltage and frequency of the islanded network within the statutory limit as long as ΔP_{inv} and ΔQ_{inv} were in the ranges of 0 to 2500 W and 0 to -480 Var, respectively at the inception of islanding. However, when ΔP_{inv} and ΔQ_{inv} were outside the determined range, the voltage and frequency of the distribution network exceeded the permissible range. Therefore, a control algorithm was developed so that the bi-directional inverter can keep the ΔP_{inv} and ΔQ_{inv} within the specified range at all times before the islanded operation.

Figure 5.22 demonstrates the flow chart of the developed control algorithm. The control algorithm started with data collection where the ΔP was obtained from the data acquisition system. The ΔP_{inv} can be calculated through equation 5.3 by using the obtained value of ΔP as the equation shown below:

$$\Delta P_{inv} = \Delta P + P_{inv} \tag{5.9}$$

where ΔP_{inv} refers to the real power mismatches of the bi-directional inverter

ΔP refers to real power mismatches between the PV systems and load

P_{inv} refers to the initial real power of the bi-directional inverter

Then, the control algorithm determined whether ΔP_{inv} was within the range of 0 to 2500 W. The bi-directional inverter was able to maintain the voltage and frequency of the islanded network within the statutory limits after its isolation from the grid when ΔP_{inv} was within the specified range. However, when ΔP_{inv} was outside the stated region, the control algorithm had to instruct the bi-directional inverter to manipulate the maximum allowable charging current by varying the P_{inv} values during grid-connected operation. This was to ensure that both the ΔP_{inv} and ΔQ_{inv} were maintained within the operational boundary before isolation started.

The control algorithm will transmit the right instruction to the bi-directional inverter via USB/RS 485 converter so that the appropriate charging current of the bi-directional inverter was selected. The reactive power mismatch, ΔQ was controlled by the internal reactive power management system of the bi-directional inverter and no external control was applied throughout the studies. The presence of the internal reactive power management system within the bi-directional inverter had eliminated the requirement of an extra control algorithm for the reactive power.

When ΔP_{inv} was greater than 2500 W or the PV output was less than the load as shown in scenario 2, and then the bi-directional inverter was instructed to reduce its charging current until the ΔP_{inv} was made to be within the range of 0 and 2500 W. However, when the ΔP_{inv} was less than 0W as described in scenario 3, then the control algorithm instructed the bi-directional inverter to increase its charging current. This process continued until the ΔP_{inv} value was brought back inside the operational boundary of the bi-directional inverter. Figure 5.23 shows the screen shot of the developed control algorithm.

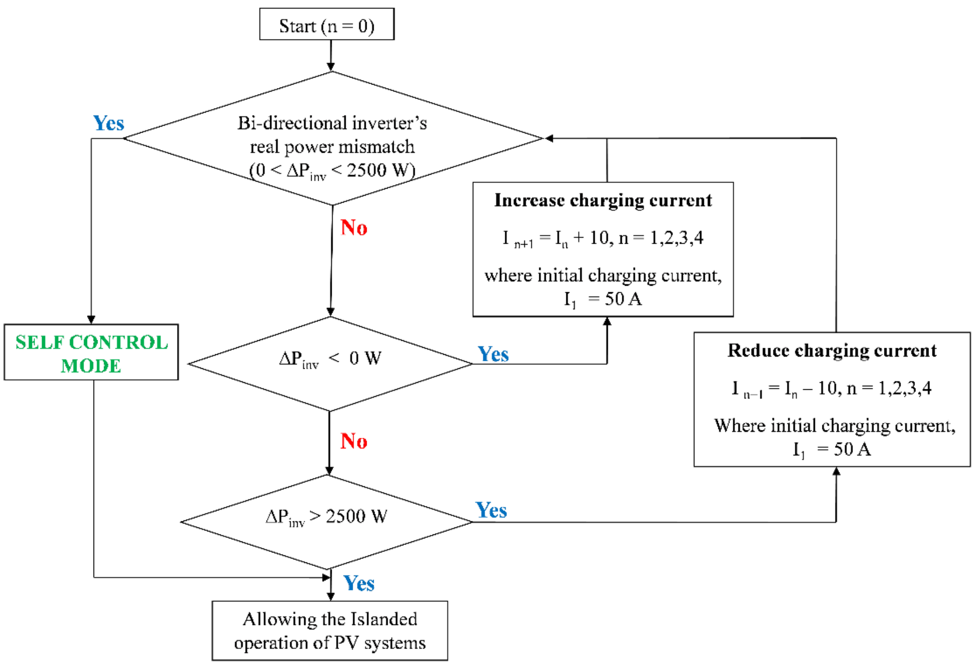


Figure 5.22 Flow chart of the proposed control algorithm

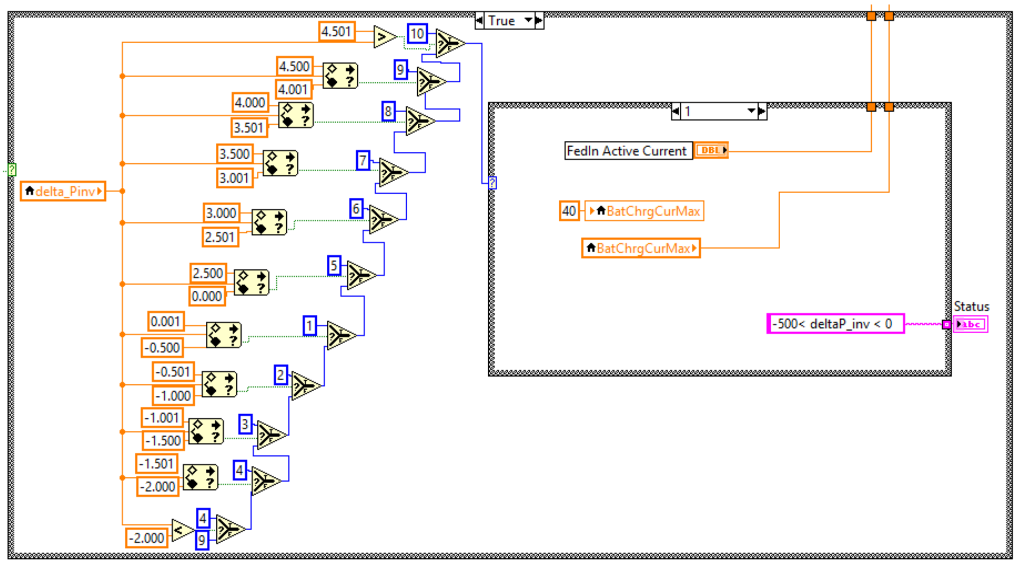


Figure 5.23 Screenshot of the developed control algorithm

5.5.1 Scenario 4: The Bi-Directional Inverter's Real Power Difference, ΔP_{inv} is Greater than 2500 W with Control Algorithm

This scenario was designed to investigate the effectiveness of the developed control algorithm when ΔP_{inv} was greater than 2500 W during the islanded operation of PV systems. In this scenario, the PV system was generating at 1170 W while the resistive load was selected to be 1900 W. Thus, resulting the power mismatch, ΔP to be 730 W. The initial value of ΔP_{inv} was at 3230 W during the grid-connected operation. When ΔP_{inv} was between the threshold of 3000 W and 3500 W, the developed control algorithm instructed the bi-directional inverter to reduce the charging current from 50 A to 30 A before the islanded operation, resulting in a reduction of ΔP_{inv} to 2200 W which was less than 2500 W.

Figure 5.24 and Figure 5.25 show the real power variation of the bi-directional inverter, P_{inv} and reactive power variation of the bi-directional inverter, Q_{inv}. After the network was discounted from the grid at t= 90s, the bi-directional inverter experienced a real and reactive power change, ΔP_{inv} and ΔQ_{inv} of 2200 W and 460 Var, respectively at the inception of islanding as shown in Figure 5.24 and Figure 5.25, respectively.

Figure 5.26 and Figure 5.27 show the frequency and voltage of the experimental low-voltage distribution network for scenario 4. It can be seen from the figures that the islanded network experienced a voltage and frequency change of 17.85 V and 0.46 Hz respectively. The figures demonstrated that the frequency and voltage changes of the islanded network were well maintained within the permissible range. Therefore, the developed control algorithm was able to allow the islanded operation of PV systems even under larger power mismatches while keeping the ΔP_{inv} and ΔQ_{inv} within the operational boundary of the bi-directional inverter.

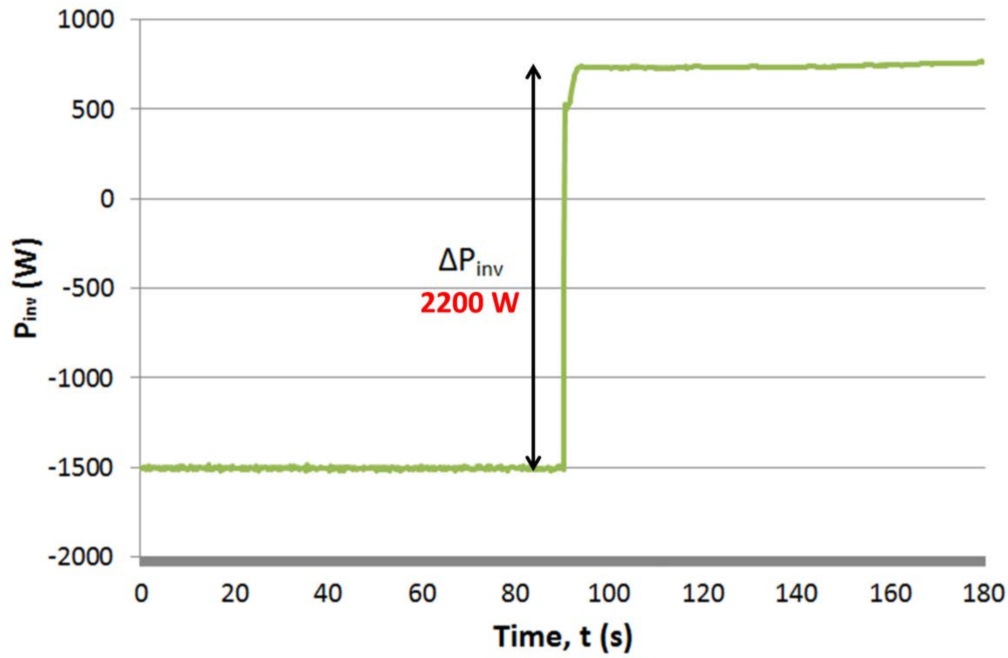


Figure 5.24 Active power, P_{inv} of the bi-directional inverter change during the transition from grid-connected operation to islanded operation

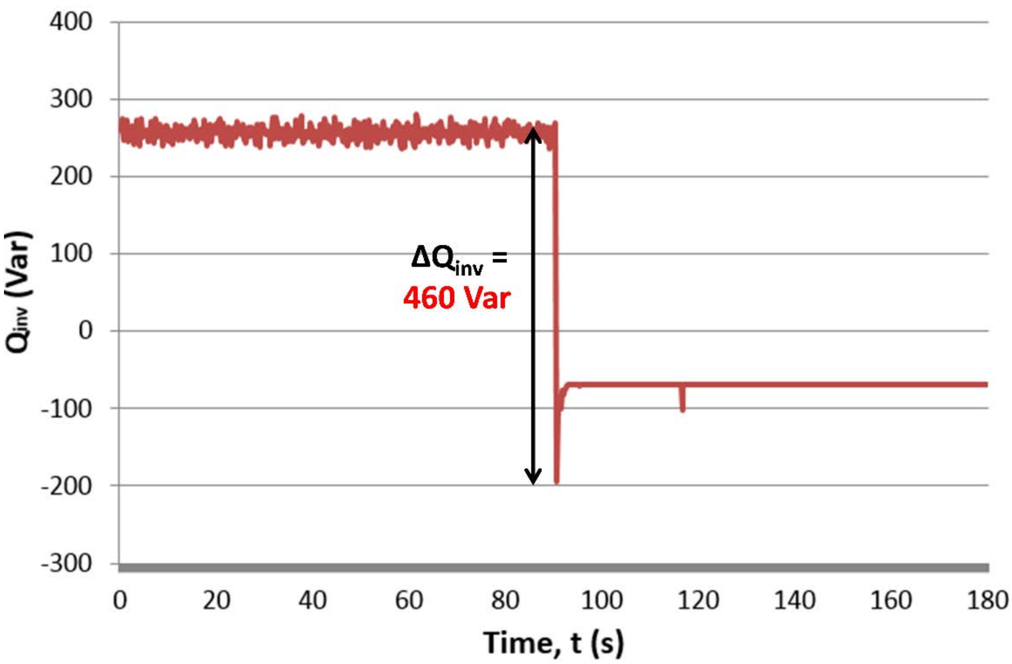


Figure 5.25 Reactive power, Q_{inv} of the bi-directional inverter change during the transition from grid-connected operation to islanded operation

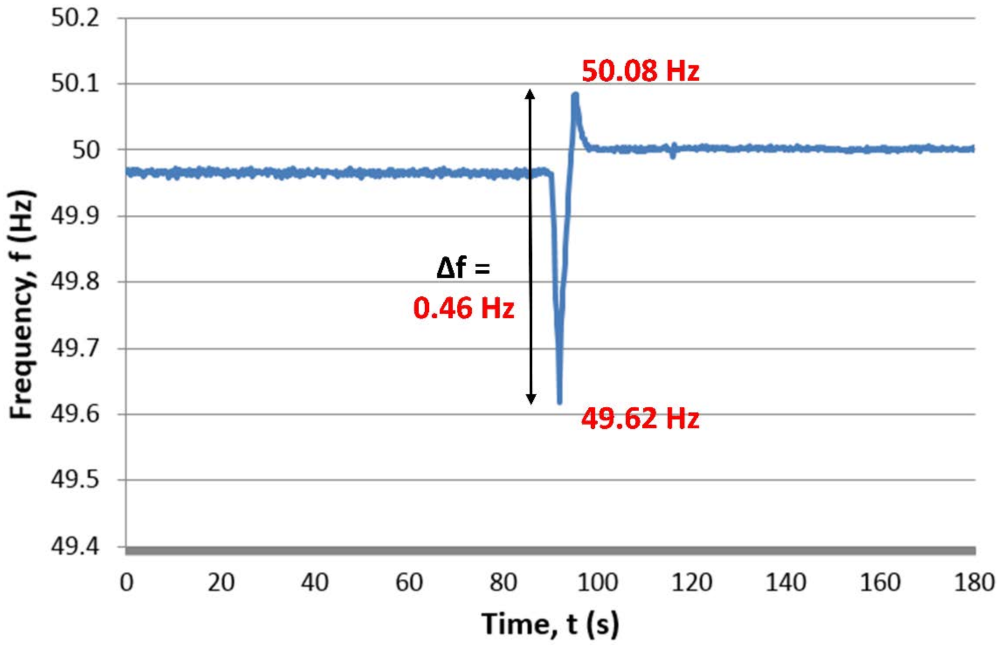


Figure 5.26 Frequency of the low-voltage distribution network in Scenario 4

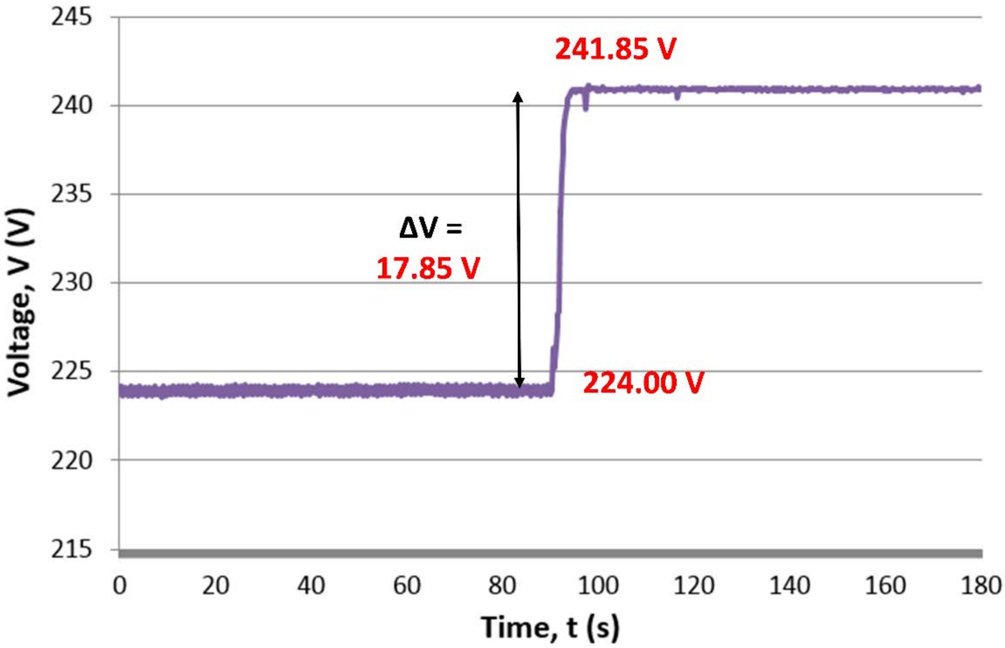


Figure 5.27 Voltage of the low-voltage distribution network in Scenario 4

5.5.2 Scenario 5: The Bi-Directional Inverter's Real Power Difference, ΔP_{inv} is Less than 0 W with Control Algorithm

Another scenario was designed to demonstrate the performance of the developed control algorithm when the ΔP_{inv} was less than 0 W. The power output from the PV systems was 3100 W and the load was 450 W, creating a power mismatch ΔP of -2650 W. The initial value of ΔP_{inv} was -150 W. Therefore, the control algorithm sends instructions to the bi-directional inverter to increase the charging power to the batteries from -2500 W to -3870 W, hence increasing the value of ΔP_{inv} to 1220 W which was within the specified range.

Figure 5.28 shows the real power changes of the bi-directional inverter, P_{inv} while Figure 5.29 shows the reactive power changes of the bi-directional inverter, Q_{inv}. Once the islanded operation began at 90 seconds, the bi-directional inverter underwent a power change ΔP_{inv} of 1220 W and ΔQ_{inv} of -340 Var as shown in Figure 5.28 and Figure 5.29, respectively. During the islanded operation, the bi-directional inverter stored the excess power of 2300 W into the batteries. Figure 5.30 and Figure 5.31 show the frequency and voltage of the experimental low-voltage distribution network for scenario 5. The islanded network experienced frequency and voltage changes of 0.78 Hz and 9.10 V, respectively after isolation. Figure 5.30 and Figure 5.31 illustrated that the frequency and voltage are restored to 50 Hz and 241.5V during the islanded operation of PV systems.

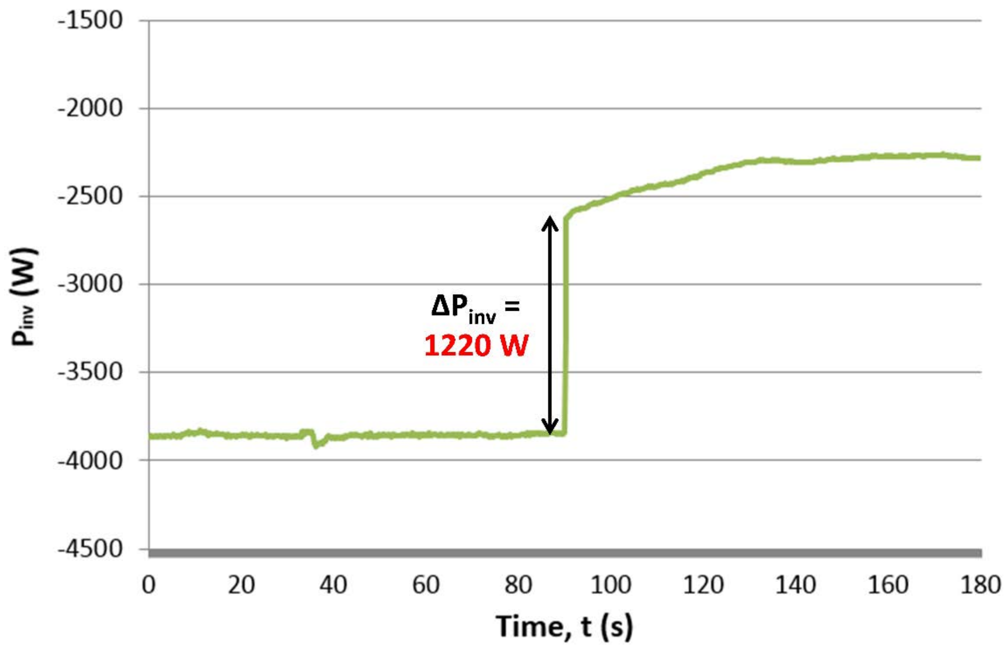


Figure 5.28 Real power, P_{inv} change of the bi-directional inverter during the transition to from grid-connected operation to islanded operation.

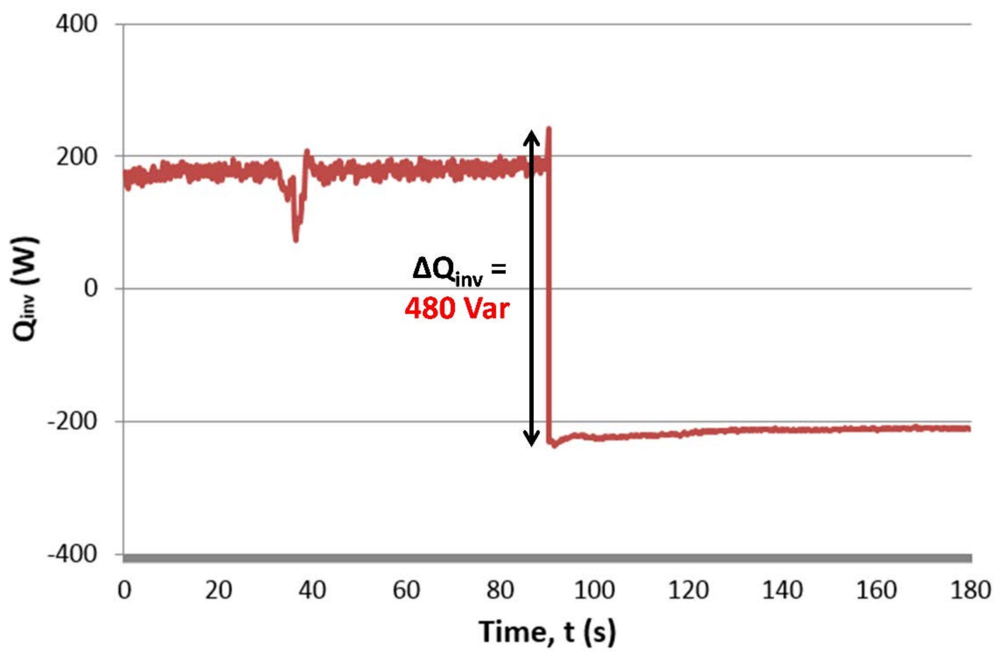


Figure 5.29: Reactive power, Q_{inv} change of the bi-directional inverter during the transition to from grid-connected operation to islanded operation

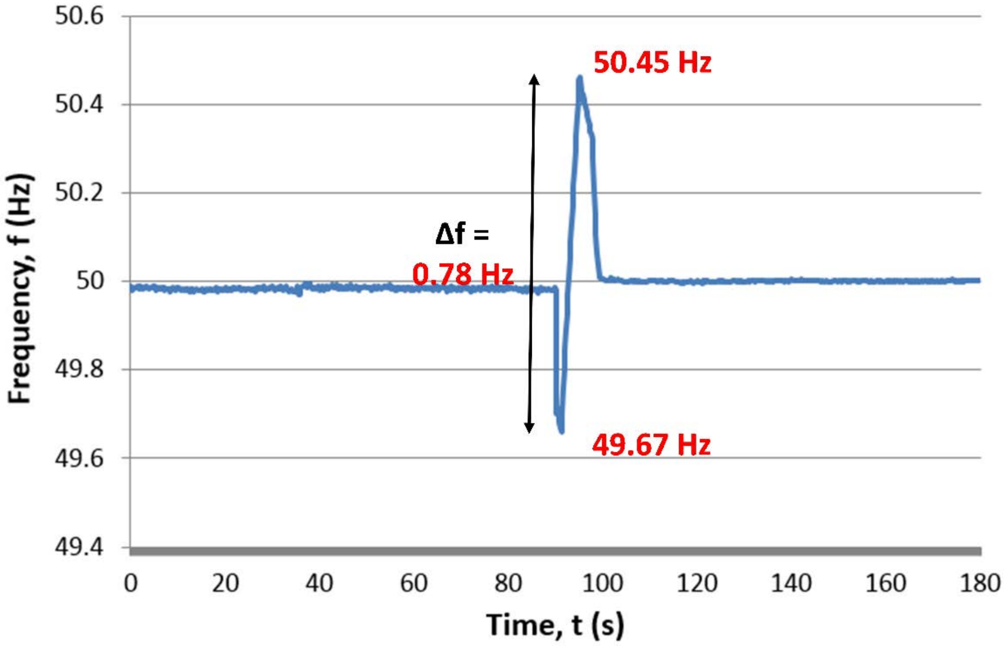


Figure 5.30 Frequency of the low-voltage distribution network in Scenario 5

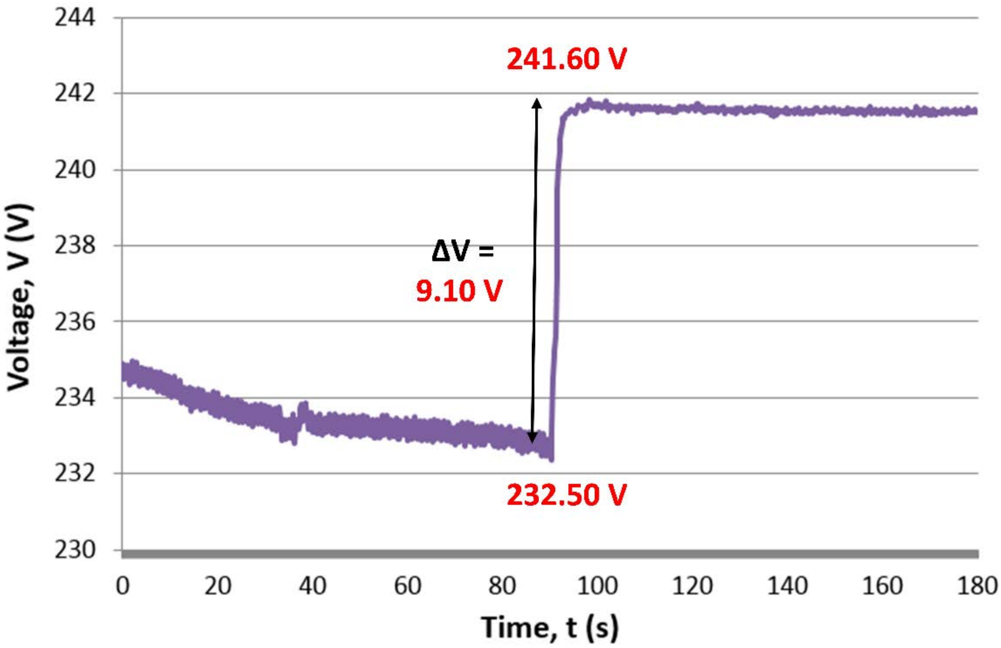


Figure 5.31 Voltage of the of the low-voltage distribution network in Scenario 5

Table 5.1 summarises the experimental results obtained from the various case studies where the voltage and frequency of the islanded network stayed within the statutory limits. Figure 5.32 depicts the operational boundary of the bi-directional inverter with the proposed control algorithm while keeping the frequency and voltage within the permissible range. It is shown that the proposed control algorithm can cope with wider power mismatches at the inception of islanding. The voltage and frequency of the islanded network was well-maintained within the statutory limits when the ΔP_{inv} and ΔQ_{inv} were inside the operational boundary.

Table 5.1 Summary of the experimental results from various case studies

Case Study	Conditions	Voltage within statutory limit	Frequency within statutory limit
Scenario 1	$0 < \Delta P_{inv} < 2500$	✓	✓
Scenario 2	$\Delta P_{inv} > 2500$ W	✗	✗
Scenario 3	$\Delta P_{inv} < 0$ W	✓	✗
Scenario 4	$\Delta P_{inv} > 2500$ W (with control algorithm)	✓	✓
Scenario 5	$\Delta P_{inv} < 0$ W (with control algorithm)	✓	✓

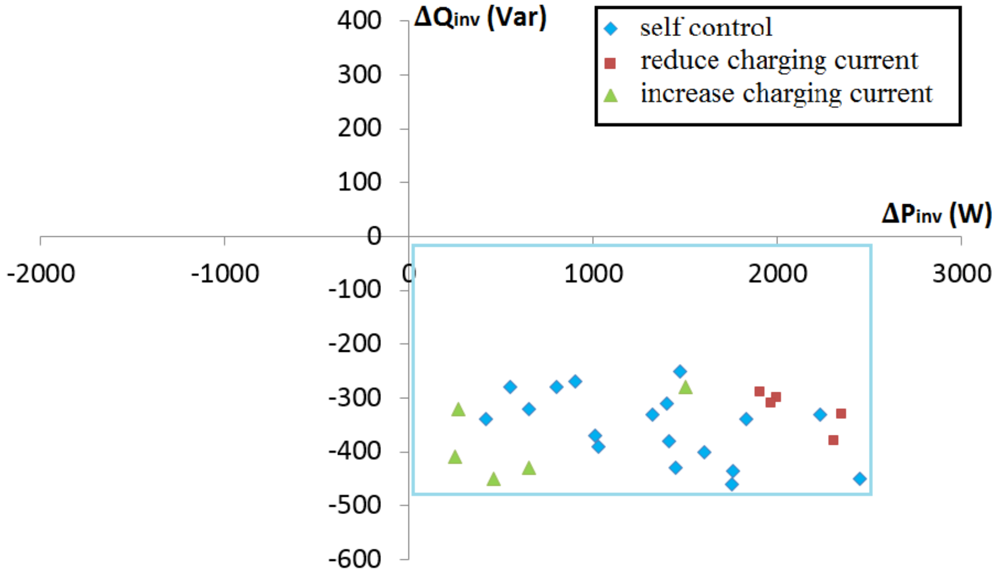


Figure 5.32 Operational boundary of the bi-directional inverter with the proposed control algorithm

5.6 Summary

The islanded operation of PV system is hard to be realised as demonstrated by the initial experimental case study due to the advancement of the anti-islanding protection mechanism embedded within the PV inverter. The proposed bi-directional inverter with batteries was able to act as a grid-forming unit during the islanded operation and regulate the voltage and frequency of the islanded network throughout the experiment. The experimental results have demonstrated that the integration of bi-directional inverter with batteries on the distribution network can allow the islanded operation with PV systems to become viable. An operational boundary for the bi-directional inverter was defined from numerous experimental results to evaluate the performance of the bi-directional inverter during the islanded operation of PV systems. The voltage and frequency of the islanded network were well maintained throughout the experiment to comply with the Malaysian standard MS IEC 60038:2006 when ΔP_{inv} and ΔQ_{inv} stayed inside the operational boundary of the bi-directional inverter. This chapter also presents a control algorithm that was developed to conduct the islanded operation of PV systems in a wider power mismatch range. The control algorithm automatically manipulated the real power for charging and discharging the batteries through the bi-directional inverter according to the values of ΔP before islanding occurs. The effectiveness of the control algorithm on conducting the islanded operation of PV systems was tested and verified on the experimental distribution network under various scenarios.

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 Discussion

Abundant solar energy has provided a great potential for the development of photovoltaic systems in tropical countries such as Malaysia. The Malaysian government has introduced a series of attractive incentives such as feed-in tariff mechanism to embrace the utilisation of green technology. Thus, the number of PV systems installed on the Malaysian distribution network are expected to increase in future. However, this has changed the power flow of the distribution network from uni-directional to bi-directional. When a fault occurs in the utility grid, an islanded network is likely to be formed. With the increase in PV systems on the distribution networks, an islanded networks consisting of PV systems are more likely to form after isolation. Under the existing regulatory framework, all the renewable energy sources are forced to be shut down after being isolated from the utility grid. Fast and reliable islanding protection systems embedded within the inverters are used to detect the occurrence of islanding and to cease the operation for safety concerns. Hence, the islanded operation of PV systems is not likely to happen.

The proposed bi-directional inverter on the islanded network with PV systems can ensure the continuity of the sectionalised distribution network even during power interruptions. This can provide a promising solution to those regions where the power interruption event is frequent. Furthermore, if the distribution network has the ability to conduct the islanded operation of PV systems, then the frequency and duration of power interruption in the electrical network can be reduced. Thus, the overall system reliability indices such as SAIDI and SAIFI can be improved. Other than that, the PV systems need not cease their operation once isolated from the grid but instead continue to energise the load during the islanded operation. This helps the consumer to fully utilise the green energy even during the islanded operation.

An experimental distribution network which consisting of a grid emulator, two PV systems and a load emulator has been designed and built in the university laboratory to investigate the feasibility of conducting the islanded operation of the PV systems. In order to conduct the islanded operation of PV systems, the voltage and frequency of the distribution network are required to be maintained within the operational limits in accordance with the Malaysian standards. This study proposes the integration of the droop-controlled bi-directional inverters with the distribution network. Experimental results of several case studies have illustrated that the capability of the bi-directional inverters integrated with batteries to perform the islanded operation of PV systems. Based on the results obtained, the operating conditions of the inverters are defined. A control algorithm is developed to allow the islanded operation of the PV systems even though the power mismatches are outside the operational boundary.

6.2 Key Findings

The key findings of this research are highlighted as follows:

- The islanded operation of PV systems is unlikely to happen. The anti-islanding protection system of the PV inverter is triggered and will immediately disconnect the PV system.
- However, the droop-controlled bi-directional inverter integrated with batteries is able to act as the grid and regulate the voltage and frequency of the distribution network during the islanded operation of the PV systems.
- The bi-directional inverter is able to mitigate the power mismatches between the grid and load demand at the inception of islanding. When the power mismatches are too large, then the bi-directional inverter is no longer able to maintain the voltage and frequency of the distribution network within the permissible range.
- An operational boundary of the bi-directional inverter is proposed to evaluate the ability of the grid-forming unit to maintain the voltage and frequency of the islanded network with the PV systems within the statutory limits.

6.3 Future Work

The existing work is tested in a single-phase experimental network. The islanded operation of the PV systems is done on a single phase system. In future, the islanded operation of the PV systems can be implemented into three phase power network.

LIST OF REFERENCES

Adham, K.N., Siwar, C., Bhuiyan, M.A.H. and Aziz, S.A.A.G., 2014. Strategic use of government procurement to spur renewable energy generation in Malaysia. *Current World Environment,* 9 (2).

Ahmad, K.N.E.K., Selvaraj, J. and Rahim, N.A., 2013. A review of the islanding detection methods in grid-connected PV inverters. *Renewable and Sustainable Energy Reviews*, 21, pp. 756-766.

Ahmad, S., Kadir, M.Z.A.A., and Shafie, S., 2011. Current perspective of the renewable energy development in Malaysia. *Renewable and Sustainable Energy Reviews*, 15(2), pp. 897-904.

Atwa, Y.M. and Saadany, E.F., 2010. Optimal allocation of ESS in distribution systems with a high penetration of wind energy. *IEEE Transactions on Power Systems*, 25(4), pp. 1815-1822.

Aziz, A. A., 2011. *Feasibility Study on Development of a Wind Turbine Energy Generation System for Community Requirements of Pulau Banggi Sabah*. Thesis. Universiti Teknologi Malaysia.

Bahrani, B., Karimi, H. and Iravani, R., 2011. Nondetection Zone Assessment of an active islanding detection method and its experimental evaluation. *IEEE Transactions on Power Delivery,* 26 (2), pp. 517 – 525.

Balaguer, I.J., Qin, L., Yang, S.T., Supatti, U. and Fang, Z.P., 2011. Control for grid-connected and intentional islanding modes of operations of distributed power generations. *IEEE Transaction Industrial Electron*, 58, pp. 147–157.

Bayliss, C., Bayliss, C.R. and Hardy, B.J., 2012. *Transmission and distribution electrical engineering*. Elsevier.

Best, R.J., Morrow, D.J., McGowan, D.J. and Crossley, P.A., 2007. Synchronous islanded operation of a diesel generator, *IEEE Transaction on Power Systems*, 22(4), November 2007.

Bower, W. and Ropp, M., 2002. *Evaluation of islanding detection methods for utility-interactive inverters in photovoltaic system*. Report IEA-PVPS T5-09, Sandia National Laboratories.

Caldon, R., Coppo, M., Sgarbossa, R., Sgarbossa, L. and Turri, R., 2013. Risk of unintentional islanding in LV distribution networks with inverter-based DG. *International 48th International Universities Power Engineering Conferences*, 2 – 5 Sept 2013 Dublin, Ireland. pp. 1 – 6.

Caldon, R., F. Rosetto, F. and Turri, R., 2004. Temporary islanded operation of dispersed generation on distribution networks. *IEEE Universities Power engineering conference (UPEC)*, pp. 987 – 991.

Chandrakar, C.S., Dewani, B. and Chandrakar, D., 2012. An assessment of distributed generation islanding detection methods. *International Journal of Advances in Engineering and Technology,* Nov 2012.

Chauhan, A. and R.P. Saini, 2014. A review of integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, 38, pp. 99 – 120.

Chen, C., Duan, S., Cai, T., Liu, B., and Hu, G., 2011. Optimal allocation and economic analysis of energy storage system in microgrids. *IEEE Transactions on Power Electronics*, 26(10), pp. 2762-2773.

Chen, W.N., 2012. *Renewable energy status in Malaysia*. SEDA

Department of Statistic Malaysia, 2013. *Compendium of environment statistics Malaysia 2013*. Department of Statistics Malaysia.

Du, Y., Guerro, J.M., Chang, L.C., Su, J.H. and Mao, M.Q. 2013. Modelling, analysis and design for a frequency droop based virtual synchronous generator for microgrid applications. *IEEE ECCE Asia Downunder (ECCE Asia),* 3 – 6 Jun 2013, Melbourne Australia, pp. 643 – 649.

Energy Commission, 2014a. *Electricity supply industry in Malaysia performance and statistical information 2012*. 1st ed. Putrajaya: Malaysia.

Energy Commission, 2014b. *Malaysia energy statistics handbook 2014*. Putrajaya: Malaysia.

Engler, A., 2004. Device for equal rated parallel operation of single or three phase voltage sources. US 6693809 B2, 17 Feb-2004.

Engler, A., 2005. Application of droops in low voltage grid. In *Int. journal of Distributed Energy Resources,* pp. 1- 15.

Fan Y.G. and Li, C., 2011. Analysis of non-detection zone of the islanding detection in photovoltaic grid-connected power system, *International Conference on Advanced Power System Automation and Protection (APAP),* 16-20 October 2011, pp. 275 – 279.

Fuangfoo, P., Meenual, T., Lee, W.J. and Chow, C., 2008. PEA guidelines for impact study and operation of DG for islanding operation. *IEEE Transaction on Industry Applications*, 44 (5), pp. 1348-1353.

Fuangfoo, P. Lee, W.J. and Kuo, M.T., 2007. Impact study on intentional islanding of distributed generation connected to a radial subtransmission system in Thailand's Electric Power System. *IEEE Transaction*, 43 (6), pp. 1491 - 1498.

Geng, H., Xu, D., Wu, B. and Yang, G., 2010. Design and comparison of active frequency drifting islanding detection methods for DG system with different interface controls. *IEEE 2nd International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 16-18 June 2010. pp. 459 - 465.

Ghaderi, A. and Kalantar, M., 2011. Investigation of influence factors on passive islanding detection methods of inverter based distributed generation. *IEEE 2nd Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, 16-17 February 2011, Tehran, Iran. pp. 217 -222.

Green Building Index, What is the green building index, 2013 [Online]. Available at: http://www.greenbuildingindex.org/index.html [Accessed: 15 May 2014]

Guerrero, J., Vasquez, J.C., Matas, J., Garcia, de V. L.G. and Castilla, M., 2011. Hierarchical control of droop-controlled AC and DC microgrids: a general approach towards standardization, *IEEE Transaction on Industrial Electornics*, 58 (1), pp. 158 -172.

Hanif, A.H., 2010. *Renewable energy and feed-in tariff*. RE/MBIPV Project team, Ministry of Energy, Green Technology and Water.

Hanif, M., Basu, M. and Gaughan, K., 2011. A discussion of anti-islanding protection schemes incorporated in a inverter based DG. *10th International Conference on Environment and Electrical Engineering*, pp. 1 - 5, 2011.

Hoppecke Batterian Gmbh & Co. KG, 2009. *Installation, commissioning and operating instructions for sealed stationary lead-acid batteries*. Mar, 2009.

IEC 61727 International Electrotechnical Commission, 2004. *Photovoltaic (PV) Systems - Characteristics of the Utility Interface*.

IEEE Standard 100-2000 Institute of Electrical and Electronics Engineers, 2000. *The Authoritative Dictionary of IEEE Standards Terms Seventh Edition*.

IEEE Standard 1547-2003 Institute of Electrical and Electronics Engineers, 2003. *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*. Jul 28, 2003.

IEEE Standard 1547.4-2011 Institute of Electrical and Electronics Engineers, 2011. *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, Jul. 20, 2011.

IEEE Standard P1366/ D8 Institute of Electrical and Electronics Engineers, 2012. *IEEE Draft Guide for Electric Power Distribution Reliability Indices*, May. 3, 2012.

Jakhrani, A.Q., Othman, A.K, Rigit, A.R.H., Samo, S.R. and Kamboh, S.A., 2012. Estimation of carbon footprints from diesel generator emissions. *2012 International Conference on Green and Ubiquitous Technology*, 30 June – 1 July 2012, Jakarta, Indonesia. pp. 78 – 81.

Johari, A., SitiHafshar, S., Hashim, H. and Ramli, M., 2013. Feed-in-Tariff (FiT) concept to promote the usage of renewable energy in Malaysia. *International Journal of Energy and Power (IJEP)*, 2 (2), pp. 33 – 37.

Johnston, D., 2013. Islanding operation of electrical systems in buildings- Control methods for voltage and frequency regulation and re-synchronisation. *Scientific Research Energy and Power Engineering*, 5, pp. 198 – 201.

Jou, H.L., Wu, J.C. Wu, K.D. Chiang, W.J. and Chen Y.H., 2005. Analysis of zig-zag transformer applying in the three-phase four wire distribution power system. *IEEE Transactions on Power Delivery*, 20 (2), pp. 1168 - 1173.

Junlakarn, S. and Ilic, M., 2014. Distribution system reliability options and utility liability, *IEEE Transactions on Smart Grid*, 5 (5), pp. 2227- 2234.

Kamel, R.M., Chaouachi, A. and Nagasaka, K., 2011. Detailed analysis of micro-grid stability during islanding mode under different load conditions. *Scientific Research Engineering Journal*, 3, pp. 508 – 516.

Kawabata, T. and Higashino, S., 1988. Parallel operation of voltage source inverters. *IEEE Transaction on Industry Applications*, 24 (2), pp. 281-287.

Khamis, A., Shareef, H., Bizkevelci. and Khatib, T., 2013. A review of islanding detection techniques for renewable distributed generation systems. *Renewable and Sustainable Energy Reviews*, 28, pp. 483-493.

Kleinberg, M.R., Miu, K. and Chiang, H.D., 2011. Improving service restoration of power distribution system through load curtailment of in-service customers. *IEEE Transactions on Power Systems*, 26 (3), pp. 1110 – 1117.

Koller, M. and Vollmin, B., 2013. Preliminary findings of a 1 MW battery storage demonstration project. *International Conference and Exhibition on Electricity Distribution (CIRED)*. 10-13 June 2013, Stockholm, Sweeden. pp. 1-4.

Kottick, D., Blau, M. and Edelstein, D., 1993. Battery Energy Storage for Frequency Regulation in an Island Power System, *IEEE Transactions on Energy Conversion*, 3 (8), pp. 455 – 459.

Kundur, P., 1994. *Power System Stability and Control*. New York, USA. McGraw-hill.

Lazarewicz, M.L. and Rojaz, A., 2004. Grid frequency regulation by recycling electrical energy in flywheel. *IEEE Power Engineering Society (PES) General Meeting*, 6-10 June 2004, Denver, USA. pp. 2038 – 2044.

Lim, Y.S., Lalchand, G. and Lin, G.M.S., 2008. Economical, environmental and technical analysis of building integrated photovoltaic systems in Malaysia. *Energy Policy*, 36(6), pp. 2130-2142.

Liu, F., Kang, Y., Zhang, Y, Duan, S. and Lin, X., 2010. Improved SMS islanding detection method for grid-connected converters. *IET Renewable Power Generation*, 4 (1), pp. 36- 42.

Londero, R.R., Affonso, C.M., Nunes, M.V.A. and Freitas, W., 2010. Planned islanding for Brazilian system reliability. *IEEE PES Transmission and Distribution Conference and Exposition (T&D)*, 19- 22 Apr 2010, New Orleans, US. pp. 1 – 6.

Lopes, L.A.C. and Sun, H., 2006. Performance assessment of active frequency drifting islanding detection methods. *IEEE Transactions on Energy Conversion*. 21 (1), pp. 171 – 180.

Mahat, P., Chen, Z. and B. Bak, B., 2010. Control strategies for gas turbine generators for grid connected and islanding operations. *IEEE PES Transmission and Distribution Conference and Exposition*. 19- 22 Apr 2010, New Orleans, USA. pp. 1 – 8.

Mango, F.D., Liserre, M. and Aquila, A.D., 2006. Overview of anti-islanding algorithms for PV systems. Part 2: Active methods. *IEEE 5th International Power Electronics and Motion Control Conference (IPEMC)*. Shanghai, China. pp. 1884 – 1889.

MS 1837:2010 Department of Standard Malaysia, 2010. *Installation of Grid-Connected Photovoltaic (PV) system*.

MS IEC 60038 Department of Standard Malaysia, 2006. *International Standard Voltages.*

Mekhilef, S. and Chandrasegaran, D., 2011. Assessment of Off-shore Wind Farms in Malaysia. *IEEE Region 10 Conferenece (TENCON)*, 2011 November 21 – 24, Bali, Indonesia. pp. 1351 – 1355.

Ministry of Energy, Green Technology and Water (KeTTHA), 2009. *National Renewable Energy Policy and Action Plan*, Ministry of Energy, Green Technology and Water Malaysia, Putrajaya.

Mishra, S., Ramasubramanian, D. and Sekhar, P.C., 2013 A seamless control methodology for a grid connected and isolated PV-diesel microgrid. *IEEE Transactions on Power Systems*. 28(4), pp. 4393 – 4404.

Moghaddam, H.J., Hosseinian, S.H. and Vahidi, B., 2012. Active distribution network islanding issues: An introduction. *11th International conference on Environmental and Electrical Engineering (EEEIC)*, 18-25 May 2012, Venice, Italy. pp. 719 – 724.
Mohamad, H., Dylan, N.H., Mokhlis, H., Karimi, M. and Bakar, A.H.A., 2013. Feasibility study of an intentional islanding operation with a new adaptive load shedding. *3rd Intentional conference on electric power and energy conversion system*, 2-4 October 2013, Istanbul, Turkey. pp. 1 – 6.

National Renewable Energy Laboratory (NREL), National Centre for Photovoltaics, 2014 [Online]. Available at: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg [Accessed: 12 December 2014].

Neto, A.C., da Silva, M.G. and Rodrigues, A.B., 2006. Impact of distributed generation on reliability evaluation of radial distribution systems under network constraints. *International Conference on Probabilistic Methods applied to Power System*. 11- 15 Jun 2006, Stockholm, Sweeden. pp.1 – 6.

Nourai, A. and Kearns, D., 2010. Batteries included. *IEEE Power and Energy Magazine*, 8 (2), pp. 49 – 54.

Pham, T.T.H., Besangesr, Y. and Hadjsaid, N., 2009. New challenges in power system restoration with large scale of dispersed generation insertion. *IEEE Transactions on Power Systems*. 24 (1), pp. 398-406.

Pusat Tenaga Malaysia, 2009. *PV Industry Handbook- Malaysian Building Integrated Photovoltaic Project (MBIPV).*

Rahimi, A., Zarghami, M., Vaziri, M. and Vadhva, S., 2013. A simple and effective approach for peak load shaving using battery storage system. *North American Power Symposium (NAPS)*, 22- 24 Sept 2013, Manhattan, USA. pp. 1 – 5.

Rajesh, V. and Kumar, C.H., 2012. Frequency control in an isolated power system by optimising a BESS technology. *International Journal of Scientific and Engineering Research (IJSER)*, 3(5), pp. 20 – 26.

Richardson, R.D. and McNerney, G.M., 1993. Wind energy system. *Proceedings of IEEE*, 81 (3), pp. 378-389.

Ropp, M.E., Begovic, M. and Rohatgi, A, 1999. Analysis and performance assessment of the active frequency drift method of islanding prevention. *IEEE Transaction on Energy Conversion*, 14 (3), pp. 810 – 816.

Ropp, M.E., Aaker, K., Haigh, J. and Sabbah, N., 2000. Using power line carrier communications to prevent islanding of PV power systems. *IEEE 28th Conference Record of Photovoltaic Specialist Conference*, 15-22 September 2000, Anchorage, Alaska. pp. 1675 – 1678.

Seca, L. and Lopes, J.A.P., 2005. Intentional islanding for reliability improvement in distribution networks with high DG penetration. *IEEE International Conference on Future Power System*, 16-18 Nov 2005, Asterdam, Netherlands. pp. 1 - 5.
Sustainable Energy Development Authority (SEDA), Sustainable Energy Development Act 2011, 2011 [Online]. Available at: http://seda.gov.my/?omaneg=000101000000010101010001000010000000000 00000000000&s=147 [Accessed: 10 Oct 2014].

Sustainable Energy Development Authority (SEDA), Announcement, 2014a [Online]. Available at: http://seda.gov.my/?omaneg=000101000000010101010001000010000000000 00000000000&y=45&s=3198 [Accessed: 10 Oct 2014].

Sustainable Energy Development Authority (SEDA), CO_2 avoidance, 2014b [Online]. Available at: http://seda.gov.my/?omaneg=000101000000010101010001000010000000000 00000000000&s=540 [Accessed: 10 Oct 2014].

Sustainable Energy Development Authority (SEDA), Feed-in Tariff (FiT) rates, 2014c [Online]. Available at: http://seda.gov.my/ [Accessed: 10 Oct 2014].

Sustainable Energy Development Authority (SEDA), Operational plants, 2014d [Online]. Available at: http://seda.gov.my/?omaneg=000101000000010101010001000010000000000 00000000000&s=539 [Accessed: 10 Dec 2014].

Sedghisigarchi, K. 2011. Power flow control of inverter based distributed generators in LV microgrids. *IEEE Power and Energy Society (PES) General Meeting*, 24-28 July 2011, Detroit, USA. pp. 1 – 6.

Sgarbossa, R., Lissandron, S., Mattavelli, P., Turri, R. and Ceretti, A., 2014. Analysis of load-induced unintentional islanding in low voltage grids with PV generators. *IEEE 15th Workshop on Control and Modelling for Power Electronics (COMPEL)*, 22-25 June 2014, Santander, Spain. pp. 1 – 8.

Shafie, S.M., Mahlia, T.M.I, Masjuki, H.H. and Yazid, A.A., 2012. A review on electricity generation based on biomass residue in Malaysia. *Renewable and Sustainable Energy Reviews*, 16 (8), pp. 5879-5889.

Singh, R., Taghizadeh, S., Nadia Tan and Pasupuleti, J., 2014. Battery energy storage system for PV output power power levelling. *Advances in Power Electronics*, 2014, pp. 1 – 11.

SMA Solar Technology. *Sunny Island 5048 Installation and instruction manual*, version 2.1.

SMA Solar Technology, *Battery management in off grid system*, Technical Brochure 6.

Smith, S.C., Sen, P.K. and Kroposki, B., 2008. Advancement of energy storage device and applications in electrical power system. *IEEE Power and Energy Society Meeting Conversion and Delivery in the 21st Century*, 20-24 July 2008, pp. 1-8.

Smith, G.A., Onions, P.A. and Infield, D.G., 2000. Predicting islanding operation of grid-connected PV inverters. *IET Proceedings of Electrical Power Applications*, 147(1), pp. 1-6.

Soo, H.L., Son, G.T. and Park, J.W., 2013. Power management and control for grid-connected DGs with intentional islanding operation of inverter, *IEEE Transactions on Power Systems*, 28 (2), pp. 1235 – 1244.

Stallon, S.D., Kumar, K.V. and Kumar, S.S., 2012. High efficient module of boost converter in PV module, *International Journal of Electrical and Computer Engineering (IJECE)*, 2(6), pp. 758 – 781.

Sustainable Energy Development Authority Malaysia (SEDA), 2012. The renewable energy roadmap, National Energy Security 2012 Conference, Closing the energy supply – Demand Gap on 28th Feb 2012.

Svensson, J., Jones, P. and Halvarsson, P., 2006. Improved power system stability and reliability using innovative energy storage technologies. *IEE 8th International Conference on AC and DC Power Transmission*, 28-30 March 2006, London, UK. pp. 220-224.

Swanson, R.M., 2006. A vision for crystalline silicon photovoltaics. *Progress in Photovoltaics: Research and Applications*, 14, pp. 122-128.

Tantimaporn, T., Srikacha, P., Loahacharoensombat, K. and Waraphok, P., 2010. Islanding operation of mini-hydro generation in real distribution network. *Proceedings of the International Conference on Energy and Sustainable Development (ESD)*, 2-4 June 2010, Chiang mai, Thailand. pp. 1- 6.

Teleke, S., Baran, M.E., Bhattacharya, S. and Huang, A.Q., 2010. Optimal control of battery energy storage for wind farm integration. *IEEE Transactions on Energy Conversion*. 25(3), pp. 787 – 794.

Tenaga Nasional Berhad (TNB), 2011. *Electricity supply application handbook*, 3rd ed. Malaysia, Distribution Division, TNB.

The Economic Planning Unit Malaysia, 2010. *10th Malaysia Plan 2011-2015*, Economic Planning Unit, Prime Minister Department, Kuala Lumpur: Percetakan Nasional Malaysia Berhad.

The Economic Planning Unit Malaysia, 2006. *9th Malaysia Plan 2006-2010*, Economic Planning Unit, Prime Minister Department, Kuala Lumpur: Percetakan Nasional Malaysia Berhad.

The Economic Planning Unit Malaysia, 2001. *8th Malaysia Plan 2001-2005*, Economic Planning Unit, Prime Minister Department, Kuala Lumpur: Percetakan Nasional Malaysia Berhad.

The Economic Planning Unit, Prime Minister's Department, *TENTH Malaysia Plan 2011-2015*, 2010 [Online]. Available at: http://www.epu.gov.my/epu-theme/RMKE10/rmke10_english.html [Accessed: 15 April 2014]

The Rakyat Post, Amcorp solar power plant largest in Malaysia, 2014. [Online] Available at: http://www.therakyatpost.com/business/2014/06/09/amcorp-solar/ [Accessed: 20 July 2014].

The Star, Selling solar power to generate income, 2014 [Online]. Available at: http://www.thestar.com.my/News/Nation/2014/08/18/Selling-solar-power-to-generate-income-NGOs-and-house-owners-in-Iskandar-can-earn-money-with-new-de/ [Accessed: 10 Oct 2014].

United Nation, 1998. Kyoto protocol to the United Nations framework convention on climate change. United Nation.

United Nation Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, 2014 [Online]. Available at: http://unfccc.int/kyoto_protocol/items/2830.php [Accessed: 22 July 2014].

US Department of Energy Information Administration, Overview of Malaysia, 2013 [Online]. Available at: http://www.eia.gov/countries/cab.cfm?fips=MY [Accessed: 15 August 2014].

Wong, J., 2011. *Power Quality Improvement Using Energy Storage for Distribution Networks With Renewables*. Thesis. Universiti Tunku Abdul Rahman, Malaysia.

Wong, J., Lim, Y.S., Tang, J.H., and Morris, E., 2014. Grid-connected photovoltaic system in Malaysia: A review on voltage issues. *Renewable and Sustainable Energy Reviews*, 29, pp. 535-545.

World solar insolation map, 2013 [Online]. Available at: http://www.altestore.com/howto/Solar-Electric-Power/Reference-Materials/Solar-Insolation-Map-World/a43/ [Accessed: 17 November 2014].

Xu, W., Zhang, G.B., Li, C. and Wang, W.C., 2007. A power line signaling based technique for anti-islanding protection of distributed generators – Part I: Scheme and analysis. *IEEE Transactions on Power Delivery*, 22 (3), pp. 1758-1766.

Ye, Z.H., Kolwalkar, A., Zhang, Y., Du, P.W. and Walling, R., 2004. Evaluation of anti-islanding schemes based on nondetection zone concept. *IEEE Transactions on Power Electronics*, 19 (5), pp. 1171-1176.

Zeinelden, H.H. and Kennedy, S., 2009. Sandia Frequency shift parameter selection to eliminate nondetection zones. *IEEE Transaction on Power Delivery*, 24 (1), pp. 486-487.

Zhu, X.C., Du, C.R., Shen, G.Q., Chen, M. and Xu, D.H., 2009. Analysis of the non-detection zone with passive islanding detection methods for current control DG system. *24th annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 15-19 February 2009, Washington DC, USA. pp. 358-363.

APPENDIX A

Technical specification of the Panasonic PV modules (VBM S230AE01)

Solar cell type	Polycrystalline
Module efficiency	14.1 %
Ambient temperature	-20 °C to + 40 °C
Relative Humidity	45 % to 95 %

Electrical data	Specification
Maximum power, P_{max}	230 (W)
Maximum power voltage, $V_{p\ (max)}$	29.4 (V)
Maximum power current, $I_{p\ (max)}$	7.83 (A)
Open circuit voltage, V_{OC}	37.0 (V)
Short circuit current, I_{SC}	8.42 (A)
Maximum over current rating, I_{max}	15.0 (A)
Maximum system voltage, V_{max}	1000 (V)

APPENDIX B

The findings from this research have been published by this author:

No.	Title	Conference	Status
1.	Allowing Islanded Operation of Photovoltaic System with the Aid of Droop-Controlled Inverter	2014 IEEE Conference on Energy Conversion (CENCON), DOI: 10.1109/CENCON.2014.6967510, pp. 248 - 253	Published
2.	Experimental Approach for Allowing Islanded Operation of Photovoltaic Systems in Malaysia	Journal of Renewable and Sustainable Energy	Under Review