CONTROL AND ANALYSIS OF ANTI-ISLANDING PROTECTION TECHNIQUES FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
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APRIL 2014

Specially dedicated to my beloved parents, brothers and sisters for their enduring love, encouragement, motivation and support.

ACKNOWLEDGEMENT

Firstly, I would like to take this opportunity to express my profoundest gratitude and deepest regards to all those who gave me the possibility to successfully complete this project. I am deeply indebted to supervisor Dr. Tan Chee Wei. I wish to express a million thanks for his exemplary guidance, monitoring and constant encouragement throughout the development of the project. In those moments of uncertainty and doubts when things used to turn dark without a clear understanding of the knowledge that their tried to share, their kind and patient way of explaining had indeed a soothing effect. The blessing, help and guidance given from time to time shall indeed carry me a long way in the journey of life on which I am about to embark in the near future.

Sincere appreciation is also extended to all the helpful and experienced members of Electrical Power Department and FKE Technicians for their guidance help and cooperation in my search of project related equipments, components, and other activities throughout the project development. I also wish to extend my sincere appreciation to Prof. Dr. Zainal Bin Salam and Assoc. Prof. Dr. Naziha Binti Ahmad Azli for their consulting in the standard and policies of Photovoltaic Gird-Connection System. Besides, I would like to thank to my fellow researchers Mr. Wong Jenn Hwa, Ms. Ngan Mei Shan, Mr. Tie Siang Fui, Dr. Ehsan Najafi and Mdm. Hanifa for their sharing and fruitful discussion.

Lastly, to all my well-wishers who had helped me both directly and indirectly, I virtually fall to short words to express my gratitude. Therefore, I end this acknowledgement with only two words **"Thank You!"** in their reminiscence.

ABSTRACT

This thesis presents a comparative study of anti-islanding detection techniques for Photovoltaic (PV) systems which also includes energy policy review and the related standards. The studied anti-islanding detection includes passive, active and a proposed hybrid technique. The proposed hybrid anti-islanding detection technique combines both active and passive detection techniques, namely Voltage Frequency Protection (VFP) and Active Frequency Drift (AFD). The passive technique is used as a primary protection, whereas the active technique is activated when an islanding situation is suspected by the passive technique. The studied anti-islanding techniques are simulated using MATLAB/Simulink simulation package. The results of simulation show that the proposed hybrid anti-islanding detection technique is able to achieve higher detection efficiency as compared to the single detection technique. The proposed technique is able to detect without having the problem as occurred to the VFP while it gains at least 50% improvement of total harmonics distortion (THD) than the AFD. In addition to that, other improvements such as, a narrower non-detected zone (NDZ), faster response time and better power quality are achieved compared to single detection technique. Besides that, the standard compliance of grid-connected PV system is reviewed as it is significant for the PV grid interconnection and distribution generation. The PV grid interconnection standards specify the criteria in utility interface and islanding prevention, in order to fulfil the requirement of MS IEC 61727:2010 and MS IEC 62116:2010 in Malaysia. Lastly, the Malaysian government's efforts in reconstructing the energy policies to promote PV are also reviewed. This study reveals that proper execution and support from local community to international level, financial aids or subsidies, technical support after installation, and PV policies and promotion plans are essential in making the PV systems development a success.

ABSTRAK

Tesis ini menerangkan kajian perbandingan di antara teknik pengesanan *anti-islanding*, berserta kajian polisi tenaga *Photovoltaic* (PV) dan piawaian berkaitan. Teknik-teknik pengesanan *anti-islanding* yang dikaji termasuk teknik pasif, aktif dan hibrid yang dicadangkan. Teknik hibrid yang dicadangkan ini merupakan integrasi daripada teknik pasif dan teknik aktif yang bernama teknik Perlindungan Voltan Frekuensi (VFP) dan teknik Frekuensi Hanyut Aktif (AFD). Teknik pasif digunakan sebagai perlindungan utama, dan teknik aktif akan diaktifkan apabila situasi *islanding* disyaki oleh teknik pasif. Teknik-teknik *anti-islanding* tersebut akan disimulasikan dengan menggunakan pakej simulasi MATLAB/Simulink. Keputusan simulasi menunjukkan bahawa teknik pengesanan hibrid *anti-islanding* yang dicadangkan ini mampu mencapai kecekapan pengesanan yang lebih tinggi berbanding dengan teknik pengesanan tunggal. Teknik hibird yang dicadangkan tidak menghadapi masalah yang berlaku di VFP, disamping dapat meningkatkan prestasi Jumlah Herotan Harmonik (THD) sekurang-kurangnya 50% daripada AFD. Tambahan lagi, peningkatan lain berbanding dengan teknik pengesanan tunggal adalah termasuk dapat mengecilkan Zon Tidak Dikesan (NDZ), masa pengesanan yang lebih pantas dan kualiti kuasa yang lebih baik. Disamping itu, pematuhan piawai bagi sistem PV sambungan grid juga dikaji kerana ia adalah penting bagi penyambungan PV ke grid dan penjanaan pengedaran. Piawaian PV sambungan grid menentukan kriteria dalam perantaran utiliti dan pencegahan *islanding*, untuk memenuhi keperluan MS IEC 61727:2010 dan MS IEC 62116:2010 di Malaysia. Akhir sekali, usaha-usaha kerajaan Malaysia dalam membina semula dasar tenaga dalam mempromosikan PV juga dikaji semula. Kajian mendedahkan bahawa perlaksanaan dan sokongan daripada masyarakat tempatan ke tahap antarabangsa, bantuan kewangan atau subsidi, sokongan teknikal selepas pemasangan, dasar PV dan pelan promosi PV adalah penting dalam menjayakan pembangunan sistem PV.

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cf	-	chopping fraction
F_{PCC}	-	Frequency at the Point of Common Coupling
Hz	-	Hertz
$I_{PV\text{-}inv}$	-	Sinusoidal inverter output current
Kd	-	derivative
Ki	-	integral
Kp	-	proportional
kVA	-	kilovolt-ampere
mH	-	MilliHenry
π	-	pi
P	-	Active power
pf	-	Power factor
P_{load}	-	Real Power of load
P_{PV}	-	Inverter Power
Q	-	Reactive power
Q_C	-	Reactive power consumed by capacitive load (VAR_C)
Q_f	-	Quality factor
Q_L	-	Reactive power consumed by inductive load (VAR_L)
Q_{load}	-	Reactive power of load
Q_{PV}	-	Inverter reactive power
t_Z	-	Dead time
V	-	volts
VAR	-	reactive power of load
VAR_C	-	volt-ampere reactive for capacitive loads
VAR_L	-	volt-ampere reactive for inductive loads
V_{load}	-	Load Voltage

V_{PCC}	-	Voltage at Point of Common Coupling
V_{RMS}	-	Root mean square voltage
W	-	Watts
ΔP	-	real power variation
ΔQ	-	reactive power variation
μF	-	MicroFarad
Ω	-	Ohm
R	-	resistive load
C	-	capacitive load
L	-	inductive load
$I_{PV\text{-}inv}$	-	PV inverter current amplitude
wPV	-	PV inverter current frequency
$Ø_{PV}$	-	PV inverter current phase angle
$i_{PV\text{-}inv}$	-	PV inverter current
K	-	accelerating gain
f_a	-	Measured frequency of voltage at the common coupling
f_{line}	-	Line frequency
jQ_{PV}	-	Reactive power from PV distribution generation
jQ_{load}	-	reactive power flowing from the PCC to the load
R_{load}	-	Local load resistive
V_{ref}	-	Reference voltage
f_{ref}	-	Reference frequency
V_{max}	-	Over voltage threshold
V_{min}	-	Under voltage threshold
f_{max}	-	Over frequency threshold
f_{min}	-	Under frequency threshold
d_f	-	forcing current frequency
f_n	-	nominal frequency
ΔV_O	-	voltage different
$V_{out\text{-}max}$	-	maximum voltage of a ripple voltage
$V_{out\text{-}min}$	-	minimum voltage of a ripple voltage
V_{ripple}	-	ripple percentage of a ripple voltage
$V_{out\text{-}avg}$	-	average voltage

f	-	Input frequency
V	-	Input RMS voltage
δ_1	-	Acceptable variance
V_{rms}	-	Root mean square voltage
s	-	Time Second
rad	-	radian
ms	-	millysecond

LIST OF ABBREVIATIONS

10MP	-	The 10th Malaysia Plan
8MP	-	The 8th Malaysia Plan 2001-2005
9MP	-	9th Malaysia Plan
AFD	-	Active Frequency Drift
AFDPF	-	Active Frequency Drift with Positive Feedback
BIPV	-	building integrated photovoltaic
BST	-	Binary Signal Transfer
CDM	-	Clean Development Mechanism
CETDEM	-	Centre for Environment, Technology and Development Malaysia
CO^2	-	Carbon Dioxide
DGs	-	distributed generation
DLC	-	Distribution Line Carrier
EC	-	Malaysia Energy Commission
EE	-	Energy Efficiency
FiTs	-	feed-in tariff
FJ	-	Frequency Jump
GHGs	-	Greenhouse Gases
GreenTech	-	Malaysian Green Technology Corporation
GT	-	Green Technology
GTFS	-	Green Technology Financing Scheme
IEC	-	The International Electrotechnical Commission
IEC 61727:2004	-	Photovoltaic (PV) Systems - Characteristic of The Utility Interface
IEC 62116:2008	-	Testing Procedure of Islanding Prevention Measures for Utility Interactive Photovoltaic Inverters

IEDs	-	intelligent electronics devices
IEEE 1574-2003	-	Interconnection Distributed Resources with Electric Power Systems
IGBT	-	Insulated-gate Bipolar Transistor
ISC E	-	Industry Standards Committee on Generation, Transmission and Distribution of Electrical Energy
KeTTHA	-	The Ministry of Energy, Green Technology and Water
LV	-	Low Voltage
MBIPV	-	Malaysia Building Integrated Photovoltaic Projects
MIDA	-	Malaysian Industrial Development Authority
MPIA	-	The Malaysian PV industry association
MPPT	-	Maximum Power Point Tracking
MS IEC 61727:2010	-	Malaysian Standard of Photovoltaic (PV) Systems - Characteristic of The Utility Interface
MS IEC 62116:2012	-	Malaysian Standard of Testing Procedure of Islanding Prevention Measures for Utility Interactive Photovoltaic Inverters
MSD	-	Main Monitoring Units with Allocated All-pole Switching Devices Connected in Series
MV	-	Medium Voltage
MW	-	Megawatt
NDZ	-	non-detected zone
OFP	-	Over Frequency Protection
OVP	-	Over Voltage Protection
PCC	-	Point of Common Coupling
PCU	-	Power Conditioning Unit
PID	-	proportional-integral-derivative controller
PJD	-	Voltage Phase Jump Detection
PLCC	-	Power Line Carrier Communication
PLL	-	Phase Lock loop

PTM	-	Malaysia Energy Centre
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
R&D	-	research and development
REs	-	renewable energies
RMS	-	Root Mean Square
RoCoF	-	Rate of Change of Frequency
SCADA	-	Supervisory Control and Data Acquisition
SEDA	-	The Sustainable Energy Development Authority of Malaysia
SESB	-	Sabah Electricity Sdn Bhd
SESCO	-	Sarawak Electricity Supply Corporation
SFS	-	Sandia Frequency Shift
SIRIM	-	Standards and Industrial Research Institute of Malaysia
SMS	-	Slip Mode Frequency Shift
SPD	-	Signal Produced by Disconnect
SREP	-	Small Renewable Energy Program
SVS	-	Sandia Voltage Shift
TC-82	-	Technical Committee of Solar photovoltaic energy systems
THD	-	Total Harmonic Distortion
TNB	-	Tenaga Nasional Berhad
U.S. EIA	-	U.S. Energy Information Administration
UFP	-	Under Frequency Protection
UL 1741	-	Standard for Inverter, Converter, and Controllers for Use in Independent Power System
UVP	-	Under Voltage Protection
VFP	-	Voltage Frequency Protection

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the age of technological mastery and rapid development of industrialization, the world energy consumption has been increasing rapidly. This scenario has led to exhaustion of resources as well as serious environmental pollution [1]. Since the fuel resources become scarce, the cost of energy resources will continue to increase in the coming decades. Such prediction created an imminent need to develop an affordable and sustainable alternative energy system around the world [2]. The development of green energy system thus gained tremendous worldwide attention in recent years and brought rapid development in distributed generation (DGs).

Solar energy or photovoltaic (PV) has become one of the most promising renewable energies (REs) sources due to the attribute of photovoltaic energy being free to harvest and will always be environmental friendly [3]. This made solar energy a prospective reliable energy supply in the future. At present, the use of solar energy can reduce the dependency on non-renewable energy. Malaysia is a country that is well suited for solar energy development due to its location, which is close to the equator. Moreover, Malaysia receives high sun light density throughout the year. Besides that, Malaysia's high level of tropical rainfall also reduces the maintenance cost of the solar panels. Hence, solar energy has a very high potential for wide-spread use in Malaysia [4]. With the introduction of 9th Malaysia Plan (9MP), more conducive environment preservation and efforts had been further promoted to support the implementation and utilization of renewable energy resources [5].

The output of PV is DC voltage, which needs to be converted back into AC voltage before being connected to the grid. The illustration of energy flow in a typical grid-connected PV system is shows in Figure 1.1. In grid-connected PV systems particularly, the connection of PV array and the balance of system to the utility grid need to fulfil the technical requirements of the utility grid's interconnection. This is to ensure high power quality as well as substantial safety interaction and high reliability of the utility. Therefore, abnormal operating conditions that could adversely affect the grid-connected PV systems have to be prevented [6]. One of the major safety issues in grid-connected photovoltaic system is to avoid unintentional operation in islanding mode. However, the issue of islanding remains a challenge in distributed generations. Therefore, the research of islanding detection technology is necessary and important.

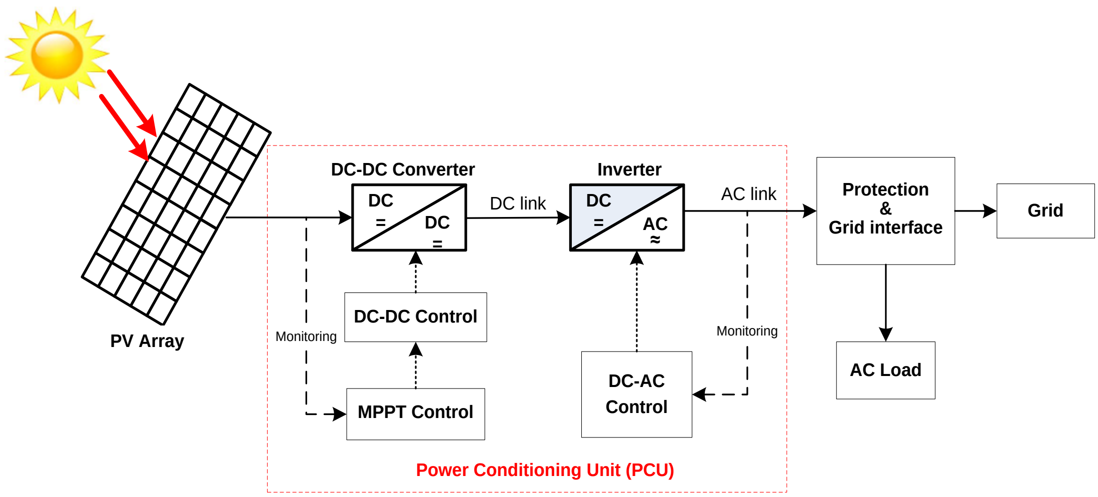

Figure 1.1: The block diagram of a PV grid-connected system

Grid interactive inverters must adhere to the voltage and frequency characteristics of the utility generated power presented in the distribution line. PV grid-connected systems should be equipped with real time monitoring unit to ensure well communication to the utility supply as well as for protection purpose.

The main reason of having anti-islanding is unintentional islanding cause deviation to the voltage and frequency of DG , which may harm the component in the systems within the islanded section. More importantly, the neutral point of inverter output is not grounded. Hence, the safety of maintenance workers will be threatened as they may not be aware of the occurrence of islanding in their service section, thus increasing the risk of electric shock [7]. In addition to that, if the system does not have synchronization equipment, and the PV system was accidentally reconnected during islanding, an asynchronous condition in which transient over-currents flow through the PV system will occur. This may result in damages to the inverters and/or protective equipment such as circuit breakers as well as to sensitive electrical equipment [8].

In case of islanding, the PV generators should be disconnected immediately from the local loads. If the grid remains connected during islanding, transient over currents can flow through the PV system inverters, consequently protective equipment such as circuit breakers might be damaged [8]. Islanding control can be achieved through inverters or via the distribution network. Inverter controls can be designed based on detection of grid voltage or measurements of impedance, frequency variation or harmonics.

1.2 Problem Statement

In utility grids, the safety, liability and quality of delivered power are highly ranked in the list of priorities. A good islanding mode control is necessary to ensure the safety of maintenance workers and to prevent the damage of equipment belonging to end users. Various anti-islanding algorithms and detection methods had been developed in the past decades [9-26]. According to the information gathered from various literatures, none of the islanding detection methods was perfect. Several limitations had been detected, which include:

i. Presence of non-detected zone (NDZ) causing possible anti-islanding detection failure.
ii. Degradation of power quality and system stability
iii. False operation in multiple DG
iv. Requirement of additional circuitry or equipment
v. High implementation cost [27].

Hence, further research and development on anti-islanding detection algorithm is inevitable in order to minimize the pitfall of the existing techniques.

Aside from all that, the standards compliance is very important for PV grid interconnection. Many standards and codes are imposed on PV source DGs. In order to meet the terms of all standards and codes make the design of PV grid-connected system difficult. Therefore, establishing a standard review for design is necessary to clearly explicate and fulfil the requirements for local application.

In addition to that, a country's energy policies are significantly important to promote widespread use of REs. For this reason, Malaysia government has restructured the country's energy policies to encourage the development of REs. Therefore, REs has been added as the fifth source of energy in the Five-fuel Diversification Policy after its introduction in 2000. The objective of the policy is to ensure that in 2005 REs contribute to 5% of the total national electricity energy mix [5]. However, by the year 2010, 10 years after the policy had been announced, REs only contributed to 0.19% in national electricity energy mix [28]. This shows that the progress of REs development was extremely slow. To further boost the use of REs in electricity generation, Malaysia Government introduced the National Green Technology Policy in 2009 and the Renewable Energy Policy in 2010, respectively. Despite the fact that there are other factors causing the slow REs development, it is especially worse when the policies do not have a clear plan, direction and guideline to achieve the goals [28].

1.3 Research Objectives

The objectives of this research are as follows:

1. To investigate the existing anti-islanding control techniques for grid-connected PV system.
2. To simulate the passive, active and to propose a hybrid anti-islanding method for grid-connected PV system using MATLAB/Simulink.
3. To review and analyse the PV grid connected energy policies and standards.

1.4 Scope of the Research

This research investigates the islanding control techniques at the end part of grid-connected PV systems. The work covers the design of an effective anti-islanding control algorithm. The proposed algorithm is a hybrid islanding protection method that combines a passive and an active anti-islanding control algorithm for islanding detection. The proposed anti-islanding control techniques for PV islanding mode control should be able to detect any sudden power disconnection from the utility grid. This is important to ensure the safety of maintenance workers and to prevent the damage of equipment of end users. This research is made thoroughly by simulation and hence there is no experimental work involved.

This research also covers the interconnection standards of PV grid-connected, focusing in the anti-islanding requirements. Finally, the effort of Malaysian government in re-structuring energy policies in order to promote PV will be review. The study focuses mainly on the policies that closely related to PV promoting, without further mentioned about others REs sources.

1.5 Research Methodology

The first step of this research is to review the past studies on anti-islanding detection methods. First, the contexts of the method principles were looked into then they were classified accordingly based on the study resources background. Both advantages and disadvantages of these methods will be identified through the review. The substances of literature review will also help to verify the analysis and discussion later. The literature sources are comprised of journal papers, conference papers, textbooks, municipal reports and official websites. In this phase, the interconnection standard of PV grid-connected that focuses in the anti-islanding requirements will also be studied. Lastly, the effort of Malaysian government to re-structure energy policies in order to promote PV also reviewed. The main issues and challenges of promoting PV identified. Programs, funding, financial scheme and incentive introduced by the Malaysian government also highlighted in this research. Finally, a conclusion was drawn concerning the effectiveness of Malaysian energy policies.

In the next stage, one passive and one active islanding detection methods will select to merge onto a newly proposed hybrid method. The proposed hybrid method is expected to overcome the problems identified in literature review part. The next step is to develop a simulation model in MATLAB/Simulink to test both the passive method and the active method selected based on the standards mentioned in the previous section. The developed model is then used to simulate the developed block and results were obtained for analysis purpose. There are several parameters data to be collected in this phase, for both selected active and passive models which including: Detection time, Run-on time, THD and NDZ. Lastly, the outcomes were used to develop a simulation model in MATLAB/Simulink for the proposed hybrid method.

Finally, all the results will be gathered for analysis and discussion. In this stage, the results of all three of the passive, active and hybrid method simulation results will be compared based on the data collected in the previous stage to verify the effectiveness of the proposed hybrid method.

1.6 Structure of Thesis

Chapter 1 introduces the development of PV grid-connected systems and the anti-islanding detection. This includes the problem statement of the PV grid-connected system, the objective and scope of this thesis, and the methodology applicable to the completion of this thesis.

Chapter 2 is an overview of the fundamentals of islanding conditions and a review of published standards of PV grid interconnection for standardization requirements. Hence, test conditions applicant to islanding detection and the standards of anti-islanding control fulfilling the requirements for local applications are clearly explicated. In addition, this chapter also reviews the energy policies promoted by Malaysians government to encourage the developments of REs, especially on PV. Therefore, programs, funding, financial scheme and incentive introduced by the Malaysian government are also highlighted. Furthermore, the main issues and challenges of promoting solar energy with energy policy are identified.

Chapter 3 is the literature review concerning anti-islanding detection techniques. In this chapter, the available islanding detection methods are reviewed and analysed. In addition to that, a comprehensive comparison among the studied methods was also made. Finally, summary and conclusions of this review are written up.

Chapter 4 presents the analysis of the existing anti-islanding protection methods. A description of the principle of passive method and active method used to develop the proposed hybrid method are detailed. The advantages and drawbacks of each method are highlighted. Furthermore, this chapter also explains the simulation constructions of the PV grid-connected anti-islanding detection method in MATLAB/Simulink simulation software. The chapter to end with the simulation results of both passive and active methods as well as the results discussion and analysis.

Chapter 5 describes the principle of proposed hybrid anti-islanding detection method. In this chapter also explains the simulation constructions of the PV grid-connected hybrid anti-islanding detection method in MATLAB/Simulink simulation software. Finally, the simulation results are discussed and analysed. Nevertheless, the results of the proposed hybrid method also compared with the single passive method and active method. The improvements of the proposed hybrid method are also highlighted.

Chapter 6 concludes the findings of this research based on the simulation results. This also includes a conclusion made concerning the effectiveness of Malaysia energy policies and establishment of regulation framework relevant to PV system. In addition, a possible direction of further research based on this work is suggested as well.

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