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ISLANDING DETECTION IN GRID-CONNECTED PHOTOVOLTAIC DISTRIBUTED GENERATION USING INVERTER DC-LINK VOLTAGE

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Chair: Prof. Ir. Norman Bin Mariun, PhD
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There is an increase in the spread of Distributed Generation (DG) in the form of solar photovoltaic (PV), wind turbines, fuel cells, etc. as renewable energy resources, giving numerous advantages if connected to the existing electric grid system. However, their integration into the grid introduces certain problems to the conventional distribution system, of which islanding detection is the most important. Islanding a situation in which a DG powers its local load while in the absence of the grid supply. The occurrence of islanding causes numerous problems to the DG, the grid and the maintenance personnel. Therefore, its occurrence must be detected within two seconds. The aim of this thesis is to study the viability of using the inverter DC-Link voltage as a parameter for passive islanding detection. The most significant shortcoming of passive islanding detection methods is the presence of large non-detection zone (NDZ), which is a region of power mismatch between the DG and the local load where islanding cannot be timely detected. For the study, a detailed model of 100 kW, 480V, grid-connected PV DG is implemented in MATLAB/Simulink. Then the response of DC-Link voltage to system load variations in islanding and grid-connected modes were studied. Furthermore, its responses to islanding on three inverter interface controllers, the constant power controller (CPC), the constant current controller (CCC) and the open-loop controller (OLC) were evaluated. The NDZ of the DC-Link voltage was determined using the UL 1741 test conditions on the IEEE 1547 anti-islanding (AI) test circuit. The effectiveness of any AI method depends on its NDZ, therefore the NDZ of DC-Link voltage was improved using the Detrending Algorithm. The effect of non-islanding grid-side faults on DC-Link voltage was equally examined. The system performance is verified with the MATLAB time-domain simulations. DC-Link voltage was found to be viable for passive islanding detection with an NDZ of +20%. The NDZ is improved to ± 1.0% by detrending the DC-Link voltage, which is a novel achievement. An AI detection system using DC-Link voltage and detrended DC-Link voltage as inputs was able to detect the occurence of islanding within 33 *ms* against the 2 seconds required by the standards. Detrended DC-Link voltage responds to each non-islanding event distinctively. To sum it up, DC-Link voltage is viable for being a parameter for passive islanding detection as it is very fast in detecting islanding, discriminative from non-islanding faults and has almost zero NDZ. The fact is validated in comparison with work done with wavelet analysis based on a neuro-fuzzy system.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGESAN PULAU DALAM GRID YANG BERHUBUNG DENGAN PENJANA PENGEDARAN FOTOVOLTAIK MENGGUNAKAN INVERTER DC-RANGKAIAN VOLTAN

Oleh

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Terdapat peningkatan dalam kemajuan Penjanaan Agihan(PA) sama ada dalam bentuk Solar Fotovoltaik (PV), turbin angin, sel bahan api, dan lain-lain sebagai sumber tenaga boleh diperbaharui, memberi banyak kelebihan jika disambungkan kepada system grid elektrik sedia ada. Walaubagaimanapun, penyatuannya kedalam grid memperkenalkan masalah tertentu kepada sistem penjanaan konvensional, yang mana paling utama sekali ialah pengesanan "islanding". Pengesan "islanding" adalah suatu keadaan dimana DG mengkuasakan beban tempatannya ketika ketiadaan bekalan kuasa grid. Hal ini mengakibatkan pelbagai masalah kepada DG, grid dan kakitangan penyelenggaraan. Oleh itu, "islanding" perlu dikesan dalam masa dua saat. Tujuan tesis ini adalah untuk mengkaji daya maju menggunakan inverter DC-rangkaian voltan sebagai parameter untuk mengesan "islanding" pasif. Kelemahan yang paling nyata untuk kaedah pengesanan islanding pasif adalah dengan kehadiran zon bukan-pengesanan (NDZ) besar, yang merupakan kawasan kuasa tidak sepadan diantara DG dan beban tempatan dimana islanding tidak dapat dikesan. Untuk kajian ini, perincian model terdiri daripada 100 kW, 480V, grid-berkaitan PV DG digunakan dalam MATLAB/Simulink. Kemudian, tindak balas DC-rangkaian voltan kepada variasi sistem beban dalam islanding dan mod grid-berkaitan telah dikaji. Tambahan, tindakbalasnya untuk islanding keatas tiga pengawal muka inverter; pengawal kuasa berterusan (CPC), pengawal arus malar (CCC) dan pengawal gelung-terbuka (OLC) dinilai. NDZ pada DC-rangkaian voltan dipilih menggunakan ujian kondisi UL 1741 pada ujian litar IEEE 1547 anti-islanding. Keberkesanan kaedah AI bergantung kepada NDZ, maka NDZ pada DC-rangkaian voltan bertambah baik menggunakan Algoritma Detrending. Kesan kepada kesalahan grid-sisi bukan-islanding keatas DC-rangkaian voltan telah diperiksa betul-betul. Prestasi sistem telah disahkan menerusi simulai masa-domain MATLAB. DC-rangkaian voltan didapati berdaya maju untuk mengesan islanding pasif dengan NDZ sebanyak +20%. NDZ meningkat kepada hampir sifar daripada detrending DC-rangkaian voltan kepada detrended DC-rangkaian voltan yang mana baru. Sistem pengesanan AI menggunakan DC-rangkaian voltan dan detrennded DC-rangkaian voltan sebagai input mampu mengesan pulau dalam tempoh 33 mili saat berbanding 2 saat yang dikehendaki oleh piawaian. detrennded DC-rangkaian voltan

bertindak balas keatas setiap kejadian bukan-islanding itu sendiri. Kesimpulannya, voltan DC-link adalah berdaya maju sebagai parameter untuk pengesanan islanding pasif kerana ia adalah sangat cepat dalam mengesan islanding, mampu membezakan kesalahan bukan-islanding dan mempunyai hampir sifar NDZ. Fakta ini disahkan melalui perbandingan kerja yang telah dilakukan dengan analisis wavelet berdasakan sisten neuro-fuzzy.

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α	Diode ideality factor
β	Inverse thermal voltage
C_A	Boost converter filter capacitor
C_{dc}	Dc capacitor
C_f	Filter capacitor
$C(s)$	PI regulator transfer function
e_{sabc}	Grid voltages
c_f	Chopping factor
D	Duty ratio
D_b	Diode rectifier
$d^*_{Q\ 1-3}$	Switching levels
f_g	Grid frequency
f_m	Frequency where the extreme phase shift happens
f , f_n	System nominal frequency
f_n , f_k	Sampled frequency
f_s	Inverter switching frequency
$F(s)$	Filter transfer function
G	Solar irradiance
$G_{inv}(s)$	Inverter transfer function
G_r	Reference solar irradiance
H , f_r	Distributed Generation inertia constant
c	Change in voltage
Δf_n	Change in frequency
ΔP	Change in power
ΔP_{DG}	Change in Distributed Generation power
ΔQ	Change in Distributed Generation reactive power
ΔV	Change in voltage
$H(s)$	Inverter transfer function
I_0	Diode reverse saturation current
I	PV cell current
I_A	Output current of PV array
i_c	Capacitor current
I_d	Inverter input current
I_D	Diode current
I_{dref}	Controller d-axis reference current
I_{dref} , I_{qref}	Inverter dq-axis reference currents

ϕ_0	Inverter default phase angle
i_{DG}, i_{inv}, i_{DGabc}	Distributed Generation current
I_{invd}	Inverter d-axis current
I_{invq}	Inverter q-axis current
$i_{j,k}$	Inverter phase currents
i_L	Load current
i_s	Grid-injected current
$I_{sc,r}$	Short-circuit current
k	Boltzmann's constant
K_f	Acceleration constant
K_I	Integral controller gain
K_P	Proportional controller gain
I_{max}	Inverter maximum peak current
L_b	Switch inductor
L_f	Filter inductor
L_{filter}	Inverter coupling filter
L_g	Grid impedance
L_s	Grid inductance
μ_b	Boost converter efficiency
m, m_{abc}	Modulation index
N	Neutral point
N_S	Number of series PV modules
N_P	Number of parallel PV modules
k_V	Open-circuit voltage temperature coefficient
P_{ac}	Inverter AC side power
P_{DG}, P_G	Distributed Generation active power
P_{dref}, P_{qref}	Reference dq-axis reference real power
P_L, P_{Load}	Island load power
Q_{1-6}	Inverter switches
Q_{DG}	Distributed Generation reactive power
Q_L	Reactive power of the load
Q_f	Quality Factor
Q_{dref}, Q_{qref}	Reference dq-axis reactive power
q	Electron charge
φ	Sliding phase angle
θ_{load}	Load phase angle

θ_m	extreme phase shift
θ_{SMS}	Slip Mode Frequency Shift phase angle
RLC	Parallel resistive, inductive and capacitive loads
R_f	Filter resistance
R_g	Grid resistance
R_P	PV cell shunt resistance
R_s	PV series resistance, grid resistance
R_{th}	PV cell Thevenin resistance
$R_{th,\,PV}$	PV module Thevenin resistance
S_{1-6}	Inverter gate pulses, switches
S_c	Capacitor bank switch
S_g	Grid-side breaker
S_{GN}, P_{DG}, P	Distributed Generation rated capacity
S_{Q1-2}, S_{Q1-4}, S_{Q1-6}	Inverter gates switching
T	Cell temperature
$T_{I_{PV}}$	Inverter current period
T_{ps}	Sandia frequency time interval
T_r	Room temperature
$T_{V_{PV}}$	Inverter voltage period
T_v, T_z	Voltage period, dead time
ω_{DG}	Distributed Generation angular frequency
ϕ_{DG}	Distributed Generation phase angle
V_0	Filter capacitor voltage
$v_{\alpha\beta 0}$	Alpha, beta voltages
V	PV cell terminal voltage
V_A	Output voltages of PV array
$V_a, V_b . V_c, V_{ijk}$	Instantaneous phase voltages
$V_{a,b,c,n}$	Phase voltages
$v_c(t)$	Carrier signal
V_C	Peak value of carrier signal
V_D	Inverter side DC voltage
V_{dc}, i_{dc}	DC voltage, current
V_{dcmes}	Measured DC-Link voltage
V_{dcref}	Reference DC-Link voltage
v_{dqo}, i_{dq0}	Voltages and currents in synchronous reference frames

V_L	Inverter line voltage
V_m	Peak value of modulating signal
$V_{\max}, V_{\min}$	Maximum, minimum voltage
v_{pcc}, V, v	Point of common coupling voltage
$V_{OC,r}$	Open-circuit voltage at STC
v_{sabc}	Inverter output voltages
Z_s	Grid impedance
$Z(s)$	Load transfer function

LIST OF ABBREVIATIONS

AC	Alternating Current
AFD	Active Frequency Drift
AFDPF	Active Frequency Drift with Positive Feedback
AFDPCF	Active Frequency Detection with Pulsating Chopping Fraction
AI	Anti-Islanding
ANN	Artificial Neural Network
ANFIS	Artificial Neuro-Fuzzy Inference System
CB	Circuit Breaker
CCC	Constant Current Control
CPC	Constant Power Control
CPCV	Constant power control variant
CV	Constant Voltage
DC	Direct Current
DG	Distributed Generation
FF	Feed Forward
GE	General Electric
IGBT	Insulated Gate Bipolar Transistor
IC	Incremental Conductance
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NDZ	Non-Detection Zone
OLC	Open Loop Control
PCC	Point of Common Coupling
PI	Proportional Integral Regulator
PLL	Phase Locked Loop
P&O	Perturbed and Observe
PJD	Phase Dump Detection
PLCC	Power Line Carrier Communication
PV	Photovoltaic
ROCOF	Rate of Change of Frequency
ROCOP	Rate of Change of Power
SPWM	Sinusoidal Pulse-Width-Modulation
SFS	Sandia Frequency Shift
SVS	Sandia Voltage Shift
SCADA	Supervisory Control and Data Acquisition
SMS	Slip Mode Frequency Shift
UL	Underwriters Laboratory DC
UOF	Under/Over Frequency
UOV	Under/Over Voltage
VSI	Voltage Source Inverter
VSR	Voltage Shift Relay

CHAPTER 1

INTRODUCTION

1.1 Research Background

There is an increase in the spread of Distributed Generation (DG) in the form of solar photovoltaic (PV), wind turbines, fuel cells, etc. as renewable energy resources giving numerous advantages if connected to the existing electric grid system. However, their integration into the grid introduce certain problems to the conventional distribution system, which has only one-directional power flow, from the power substation to the end user. With the integration of DGs power flow direction reversal may also be experienced in some feeders. This research will focus on the islanding phenomenon, being among the major problems faced by the grid integration of DGs (Ghaderi & Kalantar, 2011). Over the years, researchers have been working on different islanding detection methods, with the sole aim of finding a suitable technique that has the least non-detection zone (NDZ). NDZ is a condition of DG output power versus local load power mismatch within which islanding is not timely detectable. The integration of DG systems with the grid raises a number of relaying and protection-related issues with the AC host system. One of the most important issues is the detection of unintentional islanding of the grid-tied DG systems.

Islanding is a situation in which a DG continues powering its local load in the absence of the grid supply (Faqhruldin, 2013). This is usually caused by grid-side faults which result in negative consequences on the distribution systems including poor power quality, danger to utility maintenance personnel, and equipment damage (Akhlaghi, Ghadimi, & Akhlaghi, 2014). The IEEE 1547 Standard on Interconnecting Distributed Resources to Electric Power Systems - 2003 requires fast shut-down of grid-connected DG systems when they are isolated from the main utility power system, within a maximum of two seconds (IEEE, 2009). Methods of detecting islanding can be broadly classified into three: passive (Abo-Khalil, Al-Qawasmi, & Aly, 2013; Freitas, Huang, & Xu, 2005; H.H. Zeineldin & Kirtley, 2009), active (Freitas, Xu, Affonso, & Huang, 2005; H. H. Zeineldin & Kennedy, 2009) and communication based (H. H. Zeineldin & Salama, 2011) islanding detection techniques. The passive methods are based on measurements of DG parameters at the Point of Common Coupling (PCC) while active methods based their techniques on injection of a disturbance at the DG output at the same time monitoring some parameter(s) for the detection of islanding. Communication-based techniques rely on communication systems between the utility and the DGs using a transmitter at the grid side, that is, the power substation and receivers at the DG sites. Communication-based methods for islanding detection are very effective, with zero NDZ although very expensive to implement on small DGs. Active islanding detection techniques are complex, have negligible NDZ, but associated with power quality degradation. On the other hand, passive islanding detection techniques are simple, with no power quality issues but are associated with large NDZ (Xu, W., Mauch, K., and Martel, 2004).

Islanding detection methods that aim at reducing the NDZ using different methods have been proposed over the past years (Faqhruldin, 2013). All previous researchers on islanding detection use parameters of the PCC, the inverter AC voltage and its derivatives. However, (Vahedi, Noroozian, Jalilvand, & Gharehpetian, 2011) presented a study of islanding detection using a parameter from the DC side of the DG system, the inverter DC-Link voltage in conjunction with the PCC voltage in an active islanding detection technique. As iterated above, the active method though has little or reduced NDZ, is characterized by complexity, power quality disruption and the interference with the hardware of inverter controller structure. Another study of islanding detection using the inverter DC-Link voltage was also performed by (Banu & Istrate, 2014). In that study, the standard methods recommended by both IEEE 1547 and UL 1741 for islanding detection were not adhered to. It has therefore become necessary to conduct a study on passive islanding detection method using the inverter DC-Link voltage as an islanding detection parameter, in accordance with the standard requirements.

1.2 Statement of Problem

Most of the developed anti islanding (AI) methods focused on the inverter AC voltage and its derivatives as parameters for islanding detection, however, two research works are reported in the literature that use the inverter DC-link voltage as a parameter for islanding detection:

The research work of Vahedi *et. al*. 2011 uses the inverter DC-Link voltage in conjunction with the inverter Point of Common Coupling (PCC) voltage (V_{pcc}) in active islanding method. The strong point of this approach is the small Non-Detection Zone (NDZ) while still has the limitations of complexity, power quality issues and infringement of the inverter hardware.

Similarly, Banu & Istrate, 2014 also use the inverter DC-Link voltage in passive islanding detection method. The advantages of this approach include simplicity, absence of power quality issues, and that the technique is based on only parameter measurements. However, the method has a number of limitations including large NDZ, and non-adherence to IEEE 1547 as well as the UL 1741 AI standards.

In the light of the above, it therefore becomes necessary to conduct a study on passive islanding detection method that imbibes the advantage of the active method and enhances the shortcomings of passive method using the inverter DC-Link voltage as an islanding detection parameter in accordance with industry standard requirements.

1.3 Aim and Objectives of the Study

This research focuses on establishing the viability of inverter DC-Link voltage as a parameter for passive islanding detection and finding a novel islanding solution for grid-connected photovoltaic distributed generation using the DC-Link voltage of a Voltage Source Inverter (VSI), discriminative of non-islanding transients faults. To realize this, a detailed mathematical model of the system, consisting of PV arrays, VSI, static load and an electric distribution system is to be drived, for designing the control system. The system performance is verified by simulating the overall system in MATLAB/Simulink and SimPowerSystems. The main objectives of the research are as follows:

i. To study and validate the response of inverter DC-Link voltage to local load dynamics in islanding and non-islanding conditions using three inverter interface controller schemes.
ii. To evaluate the NDZ of the DC-Link voltage using the UL 1741 standard test conditions on the IEEE 1547 Anti-Islanding Test Circuit.
iii. To improve the NDZ of the DC-Link voltage in order to enhance its effectiveness for the detection of the occurrence of islanding using the Detrending Algorithm.
iv. To investigate the behavior of the detrended DC-Link voltage for islanding and non-islanding grid-side fault conditions.

1.3 Scope of the Thesis

The scope of the research work is given in the following:

i. Implementation of a 100 kW, 480 V, three-phase, grid-connected photovoltaic distributed generation study system in MATLAB/Simulink and Simpower systems.
ii. Performance evaluation of the DC-Link voltage to load variations in islanding and non-islanding conditions.
iii. NDZ determination and improvement of the DC-Link voltage .
iv. Evaluation of the effectiveness of the proposed NDZ reduction method in comparison with results obtained using other passive islanding detection techniques based on the IEEE 1547 and UL 1741 test conditions.

1.5 Thesis Layout

Chapter 1 (Introduction), gives the background of the research study, highlights of the significance of islanding detection in grid-connected distributed generation, classifications of islanding, statement of the problem, and objectives of the study.

Chapter 2 (Literature Review) covers the review of the previous islanding detection methods with their merits and demerits.

Chapter 3 (Methodology) outlines the study system model and its control system structure. Also, a step by step design and parameter calculations of the system and the islanding test bench in accordance with IEEE 1547 and UL 1741 are given. The implementation in MATLAB/Simulink, comprising different standard tests are discussed. The complete structure of the procedures for accomplishing the set objectives is also explained in details.

Chapter 4 (Results and Discussions) presents entirely the results obtained with the discussions of the research findings and validation.

Chapter 5 (Conclusion and Future Research) drives the overall inference on the research study, discusses the contributions of the research to the body of knowledge and outlines recommendations for future studies.

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