UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF AN ISLANDING DETECTION SCHEME BASED ON COMBINATION OF SLANTLET TRANSFORM AND RIDGELET PROBABILISTIC NEURAL NETWORK IN DISTRIBUTED GENERATION

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By

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One of the challenging issues for a grid-connected distributed generation is to find a suitable technique to detect an islanding problem. Islanding phenomena refers to the condition in which a distributed generation continues supplying power to a location at permissible voltage and frequency although electrical grid power from the electrical utility is no longer present. Its drawbacks can lead to issues such as power quality, safety of utility personal, and even power generation protection. Thus, the technique must be able to differentiate islanding from other grid disturbances and disconnect distributed generation rapidly to prevent from mentioned problems. In this work, a new islanding detection technique is proposed based on combination of Slantlet Transform and Ridgelet Probabilistic Neural Network to detect islanding conditions from other disturbance for a 250-kW PV array connected to a typical North American distribution grid and a wind farm power generation system.

The proposed strategy includes several steps. In the first step, all possible detection parameters/ signals which can be affected by islanding occurrence in the system are measured locally for islanding and non-islanding conditions. Then, by means of the Slantlet Transform theory, the matrix data extraction for any decomposition level are computed and the best of them are selected as input data to feed to an effective classifier. Next, an advanced machine learning based on is utilized to predict islanding and none islanding states. In order to train Ridgelet probabilistic neural network, a modified differential evolution algorithm with new mutation phase, crossover process, and selection mechanism is introduced. Finally, the performance of the proposed methods is also assessed using the performance indicators such as various error measurement criteria, detection rate and false alarm and compared with recent works. Furthermore, to evaluate the efficiency of the proposed modified differential evolution

for the training of ridgelet probabilistic neural network, four statistical search techniques, namely, particle swarm optimization, genetic algorithm, simulated angling, and classical differential evolution are used and their results are compared.

Results show that the proposed method is able to detect islanding conditions with 100% accuracy, 100% detection rate and 0% false alarm with detection time of less than 0.19s. Non detection zone decreases to around zero and the proposed method has the ability to detect islanding up to 0.1% power mismatch. The error measurements of the proposed method such as Mean Absolute Percentage Error, Mean Absolute Error, And Root Mean Square Error for islanding detection are less than 0.02% for ideal and noisy conditions which shows that the algorithm is not sensitive to noise. Based on the results the proposed method is accurate in detecting islanding phenomena and effective in noisy conditions.

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

PEMBANGUNAN SKIM PENGESANAN 'ISLANDING' BERDASARKAN GABUNGAN TRANSFORMASI SLANTLET DAN RANGKAIAN NEURAL PROBABILISTIK RIDGELET DALAM PENJANAAN TERAGIH

Oleh

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Salah satu isu yang mencabar untuk grid-bersambungan untuk penjanaan teragih adalah mencari teknik yang sesuai untuk mengesan permasalahan berkaitan 'islanding'. Fenomena 'islanding' merujuk keadaan di mana penjanaan teragih masih terus membekalkan kuasa ke suatu lokasi pada voltan dan kekerapan yang dibenarkan walaupun kuasa dari grid elektrik dan utiliti elektrik tidak lagi dibekalkan. Masalah ini boleh membawa kepada isu-isu seperti kualiti kuasa dijana, keselamatan terhadap pekerja utiliti, dan juga perlindungan penjanaan kuasa. Oleh itu, teknik ini mesti dapat membezakan diantara 'islanding' dari gangguan grid yang lain dan memutuskan penjanaan dari penjanaan teragih dengan segera untuk mengelakkan daripada masalah yang dinyatakan. Dalam penyelidikan ini, teknik pengesanan 'islanding' yang baru dicadangkan berdasarkan gabungan Transformasi Slantlet dan Rangkaian Neural Probabilistik Ridgelet untuk mengesan keadaan 'islanding' dari gangguan lain untuk sistem PV 250 kW yang disambungkan kepada grid pengedaran Amerika Utara yang tipikal dan penjanaan kuasa ladang angin.

Strategi yang dicadangkan ini mengandungi beberapa langkah. Dalam langkah pertama, semua parameter / isyarat pengesanan yang mungkin boleh dipengaruhi oleh kejadian 'islanding' dalam sistem diukur untuk keadaan 'islanding' dan bukan 'islanding'. Kemudian, melalui teori Transformasi Slantlet, pengekstrakan data matriks untuk mana-mana tahap penguraian dambil kira dan memilih yang terbaik sebagai data masukan kepada pengelas. Seterusnya, pembelajaran mesin canggih digunakan untuk meramalkan 'islanding' dan keadaan bukan 'islanding'. Untuk melatih Rangkaian Neural Probabilistik Ridgelet, algoritma evolusi pembezaan yang diubah suai dengan fasa mutasi baru, proses crossover, dan mekanisme pemilihan diperkenalkan. Akhir sekali, penilaian prestasi kaedah yang dicadangkan juga dinilai dengan menggunakan petunjuk prestasi seperti pengukuran alat pelbagai kriteria, kadar pengesanan dan

penggera palsu serta perbandingan dengan hasil penyelidikan lain yang terkini. Tambahan pula, untuk menilai kecekapan evolusi pembezaan yang telah dicadangkan untuk latihan Rangkaian Neural Probabilistik Ridgelet, empat teknik statistik, iaitu pengoptimuman kawanan zarah, algoritma genetik, simulasi angling, dan evolusi pembezaan klasik digunakan dan hasilnya dibandingkan.

Keputusan menunjukkan bahawa kaedah yang dicadangkan dapat mengesan keadaan 'islanding' dengan ketepatan 100%, pada kadar pengesanan 100% dan penggera palsu 0% dengan masa pengesanan kurang daripada 0.19s. Zon bukan pengesanan berkurangan kepada hampir sifar dan kaedah yang dicadangkan mempunyai keupayaan untuk mengesan 'islanding' sehingga 0.1% ketidaksamaan kuasa. Kaedah pengukuran ralat bagi teknik yang dicadangkan seperti ralat peratusan maksimum mutlak, ralat mutlak maksimum, dan ralat kesalahan maksimum akar untuk pengesanan 'islanding' adalah kurang dari 0.02% dalam keadaan yang ideal dan hingar yang menunjukkan bahawa teknik yang dicadangkan tidak sensitif kepada hingar. Berdasarkan kepada keputusan yang diperolehi, kaedah yang dicadangkan adalah tepat dalam mengesan keadaan 'islanding' dan berkesan dalam keadaan hingar.

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May the Almighty God richly bless all of you.

Declaration by graduate student

I hereby confirm that:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

f	Frequency
V	Voltage
P_{load}	Load active power
P_{inv}	Inverter active power
Q_{load}	Load reactive power
Q_{inv}	Inverter reactive power
ω_0	Resonance frequency
Q_f	Quality factor
V_{min}	Minimum voltage
V_{max}	Maximum voltage
f_{min}	Minimum frequency
f_{max}	Maximum frequency
cf	Chopping fraction
ΔC_{norm}	Resonate capacitance
$\psi_{m,n}$	Discrete mother wavelet
a_0	Real value
b_0	Real value
A	Approximation
D	Detail
E_{m,v_a}	Energy of m^{th} level of discrete wavelet transform for voltage phase-a.
$d_{m,k}$	k^{th} coefficient of m^{th} level.
D_2	Daubechies
$h_i(n)$	Low-pass filter

$f_i(n)$	Adjacent exist filter
$g_i(n)$	High-pass filter
$\frac{df}{dt}$	The value of rate of change of frequency
$\frac{dV}{dt}$	The value of rate of change of voltage
$\frac{dV_d}{dt}$	The value of rate of change of V_d
$\frac{dV_q}{dt}$	The value of rate of change of V_q
$d_i(n)$	Decomposition level
E_{ij}	Energy
μ_{ij}	Mean value
Min_i	Minimum
Max_i	Maximum
σ_{ij}	Standard deviation
$LogEn_i$	Log energy entropy
RG_i	Range
E_{signal}	Energy matrix
S_{di}^{Error}	All mean square error
$ISSD_{d_i}$	Index of ISSE for ith decomposition level.
$CINISD_{d_i}$	Index of CINISD for ith decomposition level.
$\varphi(\ldots)$	Nonlinear activation function
z_{wi}	The weight input of z_i to neuron
σ	Smoothing factor.
$R_k(z)$	Output of pattern layer
$z(t)$	Index of input vector in input layer
$\psi(.)$	Ridgelet function
$\hat{\psi}(.)$	the Fourier transform of $\psi(.)$

ψ	Admissible neural activation function.
$\psi_{\gamma}(z(t))$	Ridgelet function
a	Scale
u	Direction
b	Position
Γ	Parameter space
uS^{N}	Unit hypersphere surface of N-dimensional space.
M	The amount of classes
ω_{c}	Pattern class
$ObjF(.)$	Objective function.
X_{r}^{k}	r^{th} individual of DE population in iteration k
V_{r}^{k}	Trial vector
$X_{r1}^{k}, X_{r2}^{k}, X_{r3}^{k}$	Candidate solution.
β	Scale factor of DE.
$Tvec_{r}^{k}$	New trial vector
CR	Crossover rate
X_{best}	The best individual
β^{k}	A uniformly distributed random number.
G_{rand}	A randomly selected index
$NFF(.)$	Normalized fitness function.
$X_{ACT_{i}}$	Actual data
$X_{FOR_{i}}$	Forecast data
θ	Phase angle
V_{PCC}	Voltage at the point of common coupling.

LIST OF ABBREVIATIONS

DG	Distributed Generation
PV	Photovoltaic
SLT	Slantlet Transform
RPNN	Ridgelet Probabilistic Neural Network
DWT	Discrete wavelet Transform
MDF	Modified differential evolution
RBF	Redial basic function
PNN	Probabilistic neural network
MLP	Multilayer perceptron
LM	Levenberg-Marquardt
NDZ	Non-detection zone
PSO	Particle swarm optimization
GA	Genetic algorithm
DE	Differential evolution
IG	Interconnection guidelines
PCC	Point of common coupling
FFT	Fast Fourier transform
ANN	Artificial neural network
SVM	Support vector machine
ANFIS	Adaptive neuro fuzzy inference system
LOPF	Loss of a parallel feeder
IoT	Internet of things
CB	Circuit breaker

SFS	Sandia frequency shift
PMS	Power mismatch space
VSC	Voltage sourced converter
ROCOP	Rate of change of power output
ROCOF	Rate of change of frequency
ROCOFOP	Rate of change of frequency over power
VU	Voltage unbalance
HD	Harmonic distortion
PJD	Phase jump detection
COPCOF	Comparison of rate of change of frequency
ROCOPAD	Rate of change of phase angle difference
VS	Vector shift
PLL	Phase locked loop
AFD	Active frequency drift
FJ	Frequency jump
AFDPF	Active frequency drift with positive feedback
SVS	Sandia voltage shift
SMFSA	Slip mode frequency shift algorithm
RPEED	Reactive power export error detection based DG
PLCC	Power line carrier communication
SPD	Signal produced by disconnect
SCADA	Supervisory control and data acquisition
PMU	Phase measurement units
CWT	Continuous wavelet transform
FLC	Fuzzy logic control

PF	Positive feedback
DT	Decision tree
AIS	Artificial immune system
RFC	Random forest classifier
NBC	Naïve Bayesian classifier
IED	Intelligent electronic devices
WLAN	Wireless local area network
ISSD	Islanding signal standard division
CINISD	Cross islanding and Non-islanding standard division
DR	Detection rate
FA	False alarm
SA	Simulated annealing
RMSE	The root mean square error
MAPE	Mean absolute percentage error
MAE	Mean absolute error
MPPT	Maximum power point tracking
IGBT	An insulated-gate bipolar transistor
PWM	Pulse Width Modulation

CHAPTER 1

INTRODUCTION

1.1 Background of study

Recently, the use of alternative energy resources such as solar, wind, tidal, and biomass in the form of distributed generation (DG) into the existing power grid is growing significantly in many countries around the world due to its economic and environmental benefits [1-2]. In spite of environmental and economic benefits of them, numerous problems still need to be considered once the DGs are connected to electrical grid. One of critical problems is the protection of DG islanding. Islanding phenomena refers to the condition in which a DG continues supplying power to a location at permissible voltage and frequency although electrical grid power from the electrical utility is no longer present [3]. This electrical isolation may occur due to feeder switching, switchgear operation and or fault clearing operation, etc. Its drawbacks can lead to issues such as power quality, safety of utility personal, and even power generation protection. Thus, islanding system should be de-energized quickly.

According to existing standards for the grid connection system such as IEEE Std. 1547 [4], IEEE Std. 929-2000 [5], UL Std. 1741 [6], IEC Std. 62116 [7], and VDE Std. 0126-1-1 [8], DGs must distinguish the islanding for any probable islanding conditions and stop to energize the zone within 2 s of the formation of an island. In this regard, scholars are working extensively on unintentional islanding so as to make the islanding operation of distribution system a feasible solution by suitably addressing different methodical matters. Up to now, several methods have been proposed for this issue which are classified into remote and local based islanding detection methods. The communication or the remote technique is based on communication between the utility grid and energy resources. In spite of its better performance, the high cost and complexity of remote technique may eventually pose a barrier to its application especially for small distribution networks [9]. Instead of using remote techniques, local measurement based passive and active methods are utilized. The active methods are based on the injection of a small perturbation at the DG inverter output and examining the variation in output parameters to detect the islanding. In spite of its capabilities in reducing and or even eliminating the NZD, it has a large degradation on power quality of network, high functioning time, and increase the complexity of the system due to additional controller's or power electronics equipment [10-11]. The mainstream method is passive methods. The passive methods are based on measuring of some certain parameters such as voltage, frequency, current, and harmonic distortion of signals at the point of common coupling (PCC) and compare them with a given threshold value [10]. The passive methods are moderately suitable due to their smooth execution, practical solutions and no effect on power quality [12,13], but they have some disadvantageous such as threshold setting, large non-detection zone, high error detection rate, and low consistency in detecting the islanding correctly [14]. To overcome this issue, several computational intelligences based passive techniques have been proposed for islanding detection [9]. In recent years, in order to improve the performance of passive techniques and reduce NDZ, the passive methods based on the combination of soft computing with modern signal processing techniques has been applied. For example, a decision tree in combination with adaptive boosting has been proposed in order to improve the islanding detection accuracy [15]. However, the proposed method's sensitivity to outliners and the noisy conditions is considerable. A Bayesian classifier has been proposed for inverter-based DG to detect islanding. Owing to the high computational burden of running ESPRIT constantly on the new data windows, this technique is impractical for the implementations in the real systems [16]. Decision tree in combination with adaptive boosting method has been presented in order to improve the islanding detection accuracy [17]. However, the proposed method's sensitivity to outliners and the noisy conditions owing to nature of adaptive boosting processing is considerable. Fast Fourier transform (FFT) in combination with the immunological principle to respond to inverter islanding was presented in [18]. However, FFT is inappropriate for nonstationary signals that appear during islanding. To overcome its restrictions, FFT is substituted with wavelet features and artificial neural network (ANN) classifier for robust islanding detection, as defined in [19]. The results of proposed method show that although wavelet transform as signal processing tool has suitable time-frequency localization ability, it faces with barriers e.g. batch processing step, non-uniform frequency sub-band, less flexible and detection failure during noisy conditions.

1.2 Problem statement

Many computational intelligent methods have been used to deal with the islanding problem like artificial neural network, fuzzy logic control, decision tree, support vector machine, random forest classifier, naïve Bayesian, and data mining. For example, a deep learning with a hybrid wavelet transform and multi resolution singular spectrum entropy has been proposed for a single-phase photovoltaic system. The proposed technique has a good performance for the test cases considered in [20]. An artificial neural network-based method with a data selection technique has been offered for islanding detection of distributed synchronous generators. The concept of the time performance region has been presented to evaluate the technique performance and the none detection zone [21]. Another islanding detection method which is based on the combination of an adaptive neuro fuzzy inference system (ANFIS) and discrete wavelet transform has been proposed in [22]. In order to reduce NDZ, the proposed method uses ANFIS for selection of multi signals scenario and to avoid the threshold selection. Wavelet energy entropy as a solid indictor in combination with active frequency drift confirmation has been presented for distributed generators in distribution grids in [23]. In spite of the proposed method has a small NDZ and low time detection, it affects on power quality.

Although these techniques can detect islanding from grid disturbance, they have certain shortcoming as follows:

1) Inability to detect islanding fast due to unsuitable threshold selection, the bigger sample size, and technical challenge to upgrade the original relay system.
2) High sensitivity to overfitting; when overfitting occurs in a Neural Network (NN), the training error continues to decrease and it seems that the training process progresses, while in fact the generation capability of the NN degrades and it loses its prediction ability for unseen forecast samples.
3) Hard to implement and sensitivity to noise; basic signal processing methods such as wavelet transform, Fourier transform, S-transform are faced with with batch processing step, non-uniform frequency sub-band, less flexible and detection failure during noisy conditions.

Hence, proposing alternative methods to address the aforementioned weaknesses is necessary. In order to overcome the drawbacks of the computational islanding detection techniques, various combined methods have been proposed and utilized to solve the islanding problem, like Wavelet Pocket Transform in combination with feed forward neural network [24], probabilistic neural network in combination with phase space technique [25], autoregressive modeling in combination with support vector machine [26], and relevance vector machine [27]. In spite of the fact that these methods are more efficient in detecting islanding phenomena, regardless of their advantages, each of these methods requires improvement in terms of computational burden, response time of detection, NDZ size, and reliability. Thus, introducing powerful islanding detection techniques which can effectively solve the islanding problem are still required.

1.3 Research aim and objective

The aim of this work is to develop a technique that will solve the crucial issues e.g., islanding detection of distributed generation with special emphasis on the critical islanding events associated with NDZ of over or under voltage and over or under frequency relays. The main objectives of this work are as follow:

1. To propose Slantlet Transform as signal processing method to extract special features for islanding and non-islanding events.
2. To design and formulate a new classification algorithm known as Ridgelet Probabilistic Neural Network (RPNN) to classify islanding detection.
3. To design and formulate a new algorithm to train RPNN known as Modified differential evolution (MDE).
4. To evaluate the performance of proposed method for classification and characterization of islanding and non-islanding events under both ideal and noisy conditions.

1.4 Scope and limitation of study

The scope of this research is limited to introducing a new effective islanding detection algorithm to identify the islanding events and non-islanding events. Two standard systems namely, a 250-kW PV array connected to a 25-kV grid through a three-phase inverter (CASE STUDY I), and a power distributed generation system connecting multiple DG units (CASE STUDY II) are considered for analyzing the effectiveness of the proposed technique. Both of test systems are practical systems and are simulated in MATLAB environment. In order to evaluate the performance of the proposed islanding detection method to detect islanding in small system with one DG unit and large system with multiple DG units, these two case studies are selected. The two systems are used to evaluate the performance of the proposed algorithm to detect islanding for small and large sample size, and investigate its performance in terms of sensitivity of overfitting and noise. Moreover, these two test systems have been used by researchers in pervious related works and therefore the comparison of the proposed method with previous works can be done efficiently. This method is also adaptable with any range of DG number in any system.

In order to provide the required sensitive features of the system's behavior, a wide range of events are simulated off-line based on three criteria e.g., the functional facilities in the IEEE Sd. 1547, the testing techniques that are presented by the most manufacturers of islanding relays, and feasible topologies of operating network. Feasibility of the proposed method is also presented on the basis of response-time or detection-time. The simulated events are categorized into two conditions e.g., islanding and non-islanding conditions. Particularly, variations of active and reactive power are taken into account to produce a large set of islanding events. The range of active power mismatch between DG capacities and local loads was assumed to be from 0% up to ±30% and reactive power mismatch was considered from 0% up to ±5%, which are used to simulate different operating conditions. The various possible non-islanding events that can falsely trigger islanding detection are short-circuit faults, loss of a parallel feeder (LOPF), load switching, capacitor switching, non-linear loads switching, and starting of large motors. Each of these non-islanding scenarios have been simulated to verify the accuracy of the proposed technique. To validate the proposed islanding detection algorithm, the performance of the proposed algorithm (RPNN) is compared with some other popular classifier, for training in differentiating the islanding event from other system disturbance events.

1.5 Thesis layout

The remaining chapters of the thesis are briefly described as follows:

Chapter 2 is a literature review providing an overview of the definition of islanding, its detection schemes and their issues as reported in literatures. Then, an overview of performance of soft computing methods proposed in order to detect islanding events will be presented.

Chapter 3 describes the design and development an innovation islanding detection technique based on combination of Slantlet transform and Ridgelet probabilistic neural network in order to detect islanding conditions from other disturbance for two case studies. The methodology diagram of the proposed strategy is introduced at the beginning. Then, a brief overview of Discrete Wavelet Transform a modern and Slantlet Transform strategy are presented. Next, feature extraction strategy is introduced for each of case study. Afterward, the structure of PNN and the proposed method e.g., Ridgelet Probabilistic Neural Network (RPNN) are demonstrated. Subsequently, the execution procedure of the proposed islanding detection technique is presented for both case study.

Chapter 4 presents the simulation results, discussions, and comparisons of the proposed algorithm with islanding detection methods reported in the literature. In this section, two case studies namely, a 250-kW PV array connected to a 25-kV grid through a three-phase inverter (CASE STUDY I), and a power distributed generation system connecting multiple DG units (CASE STUDY II) are considered for testing, validation, and show the efficacy of the proposed method. Finally, the conclusions regarding the implementation of the proposed islanding detection technique are drawn and suggestions for future research are given in chapter 5, respectively.

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LIST OF PUBLICATIONS

Journals

Ahmadipour, M., Hizam, H., Othman, M. L., Radzi, M. A., & Nikta, CH. ***(2019).*** A Novel Islanding Detection Technique Using Modified Slantlet Transform in Multi-distributed Generation. ***International Journal of Electrical Power & Energy Systems***, 112, 460-475. (ISI Thompson, IF: 4.418) (Q1).

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Conferences

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