Modeling of Islanding Detection for Inverter-Based Distributed Generator using Nonlinear System Identification Approach

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Abstract— *In this paper, the system identification modeling of islanding protection of distributed generator based inverter is proposed. The goal of this research is to study the behavior of islanding detection scheme via the model which obtains from the nonlinear system identification. The islanding phenomenon is simulated and anti-islanding scheme of inverter has been modeled. The waveform of grid current and PCC voltage as input of model and inverter current as output of model have been collected for system identification processing. The six scenarios of experimental condition is performed and their anti-islanding modeling is derived. The suitable model for represent the anti-islanding is derived by nonlinear model with sigmoid and wavelet estimators. The derived mathematical model of inverter under islanding is analyzed for understand anti-islanding phenomena, islanding detection techniques, and model based islanding detection for future work.*

***Keywords*— Islanding detection, modeling.**

1. INTRODUCTION

A photovoltaic system is an attractive renewable energy for Thailand because of high potential of solar irradiation about 18 MJ/m^2/day. Furthermore, it is envisaged that with the government incentive on adders on electricity from renewable energy like solar PV, more households will be attracted to produce electricity in small capacity less than 10 kW VSPP (very small power producer). Then a possibility to expand the roof-top grid-connected units in Thailand draw attention to the study of single phase PV-grid connected systems. In connecting PV-based inverter to the power system, inverter is one of the enabling key to achieve the utility regulation such including voltage level, harmonic content and protection function on under/over-voltage, under/over frequency, phase/ground over-current, synchronizing check and anti-islanding. One of the most important issues is the development of the efficient protection technique against a phenomenon known as islanding. An Islanding phenomenon is the condition of a distributed generation (DG) generator continuing to power a location even though power from the electric utility is no longer present. The situation may cause an electrical shock hazard to service personnel operating on the islanding network section while it has been supposedly shut down through separating it from the main power station. With this reason, anti-islanding is a one essential function in for testing standard of connection DG to the utility follow as Thailand utility's code, IEEE929-2000, IEEE1547-2003 and IEC62116. The standard is requirement that inverter must be cease energized the power into the system within requirement duration. Then various kinds of anti-islanding detection methods is studied to understand the behavior of each methods [1]. The existing methodologies of islanding detection can be divided into two main groups such remote and local. Local techniques can be subdivided in passive and active as shown in Fig 1 [2]. Remote techniques for detection of islands are based on communication between the utility and the DG. Remote techniques do not have a non-detection zone but this technique is not appropriate implementation for small DG systems which no need the communication channels to the utility. Passive detection methods have a large non-detection zone (NDZ) and slow detection. In active methods disturbance signal is applied to certain parameters at the PCC so that islanding condition can be detected. Active methods involve some kind of feedback technique or control mechanism that detects changes in the frequency or voltage at the PCC. Active detection methods should be also used to decrease the size of NDZ. But the main disadvantage of active methods is the injecting of a disturbance signal into the grid, this is undesirable for the utility and its customers.

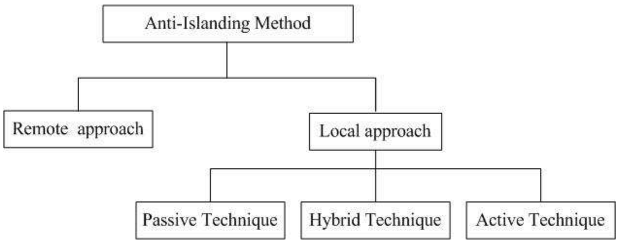

Fig. 1. Anti-islanding classification.

In applications, each specific methodology has its own advantages and drawbacks. Therefore, in designing anti-islanding protection devices, both mathematical theory and measurements of PV parameters plan an important

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role in success of the entire process. Then the behavior of inverter under islanding condition and the advance islanding detection techniques to compensate the problem and increase efficiency of inverter is interested. In recently, a novel method like model based prediction control (MPC) which uses the model for prediction output and generate control signal is attractive for control system including islanding detection area. The method is operated by using the model to detect islanding with less non-detection zone, fast detection, and low mistake. In addition this technique is performed by without the deliberate any signal into the power system in as same manner of passive techniques. However, the most important tool for model based anti-islanding detection is a mathematical modeling of islanding condition. There are several approaches to acquire the anti-islanding modeling such as PSPICE, Simulink Matlabl, PSCAD/EMTDC, state space averaging of islanding phenomena [4-10]. However all of them need to know algorithm and information inside which is not possible for commercial products. In different approach, experimental route is doesn't need to know the inside specific data of controller and it can be applied for any kind of inverter. With this reason, the system identification approach is studied in this paper [11]. The aim of this paper is to achieve the modeling of anti-islanding algorithm which can be useful for model based control system in the future work.

2. ISLANDING DETECTION TECHNIQUES

In order to establish mathematical model of PV inverter under islanding condition. PV inverter is considered as a current source and the utility grid is simplified as a voltage source as shown in Fig.2.

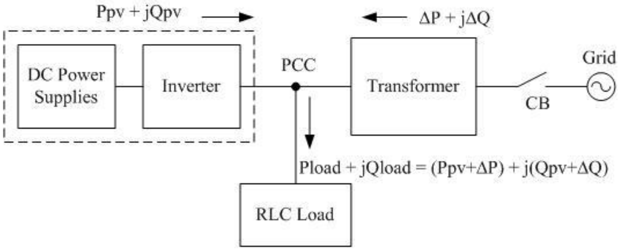

Fig. 2. Schematic configuration of PV system.

Prior to study the different method of anti-islanding, it is important to focus on two key features in order to understand the islanding phenomena. The first one is called "Non-detection zone" (NDZ), which can be defined as the range in which an islanding detection scheme under test fails to detect this condition. The second one is associated with the nature of loads, which from a conservative point of view to the difficulties that some detection techniques have to identify a islanding condition with such loads. In case of parallel load the value of quality factor is follow as equation (1) where Q_f is quality factor, R is effective load resistance, C is effective load capacitance, L is effective load inductance, P is real power, Q_c is capacitive reactive power and Q_L is inductive reactive power and for resonance case of RLC load $Q_L = Q_c = Q_{var}$ as written in equation (2)

$$Q_f = R\sqrt{\frac{C}{L}} = \frac{1}{P}\sqrt{Q_L Q_C} \quad (1)$$

$$Qf = \frac{Q_{\text{var}}}{P} \quad (2)$$

In order to derive an anti-islanding modeling, each types of islanding detection is studied as follow

a) Remote approaches

Remote approaches for detection of islands are based on communication between the utility and the DG. Remote techniques do not have a non-detection zone but this technique is not appropriate implementation for small DG systems which no need the communication channels to the utility.

b) Local approaches

Local approaches are based on the measure of some parameters on the distributed generators side. There are two subgroup of local techniques follow as passive method, based on the monitoring of these parameters and active methods, which deliberately introduce disturbance at the output of inverter and observe whether parameters are affected.

i) Passive techniques

Passive techniques are based on islanding detection through monitoring of parameters such as voltage, current, frequency and/or their characteristics. The interruption for cease energized power from inverter is controlled when these parameters are changed beyond to the limitation.

ii) Active techniques

Active techniques intentionally injected disturbances at the output of the inverter to determine the affect toward voltage, frequency, impedance and their related parameters in which to evaluate that the grid has been disconnected and the inverter is isolated from the load. The advantage of active techniques is the eliminating NDZ and high detection but the power quality is deteriorated and power system instability in particular with high amount of distributed generators.

Various kind islanding detection methods are studied including four remote approaches, five passive techniques and ten active techniques. An explanation of islanding strategies in term of principle, advantages and disadvantage are summarized in Table 1 [12-17].

Table 2. A comparison of islanding detection techniques

No	Detection method	How to operate	Advantage	Disadvantage
1	**Remote Techniques**			
1.1	Impedance insertion	Insertion of a low impedance load (capacitors bank) connected to PCC when utility breaker open and Disturbance causes a phase change and sudden variation of the resonant frequency is detected by OUF limits.	Capacitor bank also used for reactive compensation.	Expensive to implement and time needed to insert the capacitor bank after grid disconnection could not meet stadandards.
1.2	Power line carrier communications (PLCC)	Uses power line as a communication channel by transmit continuous low energy signal between trasmsmitter and receiver	Output power quality is not degraded, No NDZ and ability operate in areas with high density of DG	Cost of receiver (DG) and transmitter (grid) is too high.
1.3	Signal produced by disconnect (SPD)	communication between the network and inverter to avoid islanding but different from PLCC in type of transmission media	In point of view of energy management, this method has advantage of additional supervision and control of both DG and grid.	High cost which increases with every DG connected to the network
1.4	Suepvisory control and data acquisition (SCADA)	use a wide communications networks and sensors to control and monitor the grid conneted equipment	Highly effective to detec islanding, eliminating NDZ	Too expensive and requiring a large number of sensors and additional features.
2.1	**Local Techniques (Passive Method)**			
2.1.1	Over/Under voltage OUV Over/Under frequency OUF	Detection on the change of ΔP, ΔQ	Low cost option	Large NDZ and the variability or unpredictable of reaction time.
2.1.2	Voltage phase Jump	Error between of the new phase voltage and output current inverter.	Effective for multiple inverter and not affect to transient response-PQ	Choose threshold level difficult especially with starting motors.
2.1.3	Detection of voltage and current harmonics	Detection on the THD at PCC	Operate with a wide range of conditions and multi inverter	Costly for small PV inverters
2.1.4	Detection based on state estimators	Based on applying a voltage oriented control combined with the use of resonant controlles and Identify islanding from estimate (Kalman filter) and measures values.	Being a passive method which does not affect the system power quality, low NDZ and high rate detection	More complexity from the programming and algorithm.
2.2.5	Cross Correlation	Use crosss correlation to evaluate two time varaible signal for detection islanding conditions.	Less time to disconnect	Upto speed of microcontroller
2.2	**Local Techniques (Active Method)**			
2.2.1	Impedance measurement	To detect Impedance change (dv/di) at the output of inverter. When disconnected utility is supposed to have low impedance.	An Extreme small NDZ for a single PV inverter.	Effective decrease as number of inverters connected to grid increases and voltage suffer from disturbance from inverter current
2.2.2	Harmonic injection/detection of harmonic	Injecting a specific curent harmonic at PCC can be detected when the grid impedance is lower than load impedance at harmonic freqeucny	Same as harmonic detection but disadvantage can be overcome if subharmonic signals are injected instead of high order harmonics.	Detection problems are not definitvely solved unless the amplitude of the injected harmonics is very small.
2.2.3	Sliding mode Frequency Shift (SMS)	Based on varying the inverter output freqeuncy by controlling the phase of inverter current.	Easy to implement, small NDZ , effective with multiple inverter and compromise with output power quality and transitory response	High penetration level can effect PQ and transient response
2.2.4	Active Freqeuncy Drift (AFD)	Elimiate the phase error between the V_{PCC} and inverter output current which affect to frequency and can be detected by OUF.	Implement able on micro controller and easy	Small degradation of PQ. Need agreement the direction of freqeuncy bias.
2.2.5	Frequency Jump	Modification of AFD, similar to impedance estimation techniques.	The pattern is sufficiently sophisticated and effective in single inverter	Loses effectiveness when connecting multiple inverters unless the frequencies dithering between inverter are synchronized.
2.2.6	Variation of active power and reactive power	Use relationship bewteen voltage e and active power, frequncy and reactive power for detection	It can be develop to another method based on measuring grid frequency	Can generate false detections when several inverters are connected at same point .
2.2.7	Sandia Frequency Shift (SFS)	Frequncy of V_{PCC} positive feedback and detects with OUF.	Easy to implement like SMS	High penetration level can effect PQ and transient response
2.2.8	Sandia Voltage Shift (SVS)	Amplitude of V_{PCC} positive feedback and detected by OUV.	Implement able on micro controller and easy	Small reduction of power quality and PV effieicency due to MPP control.
2.2.9	General electric frequency shemes (GEFS)	injects a current disturbance and evaulates the effects on PCC.	Easy to implement, reduce NDZ low impact to PQ and robust against grid disturbance.	The injection of disturbance signals (frequency ans voltage) requires be as small as possible.
2.2.10	Mains monitoring units with allocated all-pole switching devices connected in series (MSD)	Using two monitoring devices in parallel, connected to two seires with switch devices for voltage, frequency and impedance of the grid.	Small NDZ, redundancy monitoring and regular self-evaluation.	High probability of interference with other device including the grid itself.

3. MODELING VIA SYSTEM IDENTIFICATION

With the aim of obtaining mathematical model of islanding condition, System identification process is proposed by measuring the input/output from system [18-19]. Most dynamical systems can be better represented by nonlinear models. One of the most frequently studied classes of nonlinear models are called block-oriented models, which consist of the interconnection of linear blocks and nonlinear block. There are various kinds of nonlinear system identification methods owing to varied positioning of interconnection, types of linear functions and nonlinear functions. Hammerstein-Wiener Model appropriate for describe complex system like inverter based PV system [20]. This model describes dynamic systems using input and output static nonlinear blocks in series with an output-error type of dynamic linear blocks which are distorted by static nonlinearities. The following structure describes the Hammerstein-Wiener, shown in Fig.3.

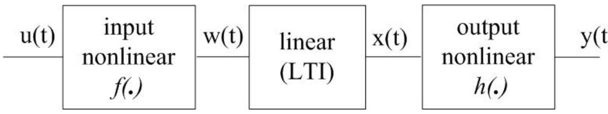

Fig. 3. Structure of Hammerstein-Weiner model.

The following general equation describes the Hammerstein-Wiener structure are follow equations (3)

$$\left.\begin{aligned} w(t) &= f(u(t)) \\ x(t) &= \sum_{i}^{nu} \frac{B_i(q)}{F_i(q)} w(t-n_k) \\ y(t) &= h(x(t)) \end{aligned}\right\} \quad (3)$$

which u(t) and y(t) are the inputs and outputs for the system. w(t) and x(t) are internal variables that define the input and output of the linear block. In linear block, there are polynomials B and F contain the time-shift operator q, essentially the z-transform which be expanded as in equation (4). u_i is the ith input, nu is the total number of inputs.

$$\begin{aligned} B(q) &= b_1 + b_2 q^{-1} + ... + b_n q^{-b_n+1} \\ F(q) &= 1 + f_1 q^{-1} + ... + f_n q^{-f_n} \end{aligned} \quad (4)$$

b_n and f_n are input coefficients. nk_i is the ith input delay that characterizes the delay response time and e(t) is the error signal. The order of the model is the sum of b_n and f_n . This should be minimum for the best model. The Hammerstein-Wiener Model compose of the input and output nonlinear block which contain nonlinear functions f(•) and h(•) that corresponding to the input and output nonlinearities. The both nonlinear blocks are implemented using nonlinearity estimators. Inside nonlinear block, five nonlinear estimators are follow as

i) The dead zone (DZ) function generates zero output within a specified region, called its dead zone or zero intervals. The lower and upper limits of the dead zone are specified as the start of dead zone and end of dead zone parameters. Dead zone can define a nonlinear function y = f(x), where f is a function of *x*, It composes of three intervals as following in equation (5) when x has value between a and b, then output of function equal to $F(x)=0$ this zone is called as zero interval.

$$\left.\begin{aligned} a<x<b \quad & f(x)=0 \\ x<a \quad & f(x)=x-a \\ x\ge b \quad & f(x)=x-b \end{aligned}\right\} \quad (5)$$

ii) Saturation (ST) estimator can define a nonlinear function y = f(x), where *f* is a function of *x*, It composes of three intervals as the following characteristics in equation (6)

$$\left.\begin{aligned} x>a \quad & f(x)=a \\ a<x<b \quad & f(x)=x \\ x\le b \quad & f(x)=b \end{aligned}\right\} \quad (6)$$

The function is determined between a and b values and always call this interval as linear Interval

iii) Piecewise linear function (PW) is define as a nonlinear function, y=f(x) where f is a piecewise-linear (affine) function of x and there are n breakpoints (x_k,y_k) which k=1,...,n. y_k = f(x_k). f is linearly interpolated between the breakpoints. y and x are scalars.

iv) Sigmoid network (SN) activation function

Both of sigmoid and wavelet network estimators use the neural network composing an input layer, an output layer and a hidden layer using wavelet and sigmoid activation functions ash shown in Fig.4.

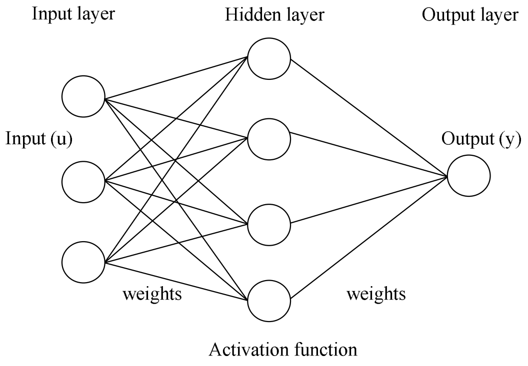

Fig. 4. Structure of sigmoid and wavelet network estimators.

The sigmoid network nonlinear estimator combines the radial basis neural network function using a sigmoid as the activation function. This estimator is based on the following expansion in equation (7)

$$y(u) = (u-r)PL + \sum_{i}^{n} a_i f((u-r)Qb_i - c_i) + d \quad (7)$$

when u is input and y is output. r is the regressor. Q is a nonlinear subspace and P a linear subspace. L is a linear coefficient. d is an output offset. b is a dilation coefficient., c a translation coefficient and a an output coefficient. f is the sigmoid function, given by the following equation (8)

$$f(z) = \frac{1}{e^{-z}+1} \tag{8}$$

v) Wavelet network (WN) activation function

The term wavenet is used to describe wavelet networks. A wavenet estimator is a nonlinear function by combination of a wavelet theory and neural networks. Wavelet networks are feed-forward neural networks using wavelet as an activation function, based on the following expansion in equation (9)

$$y = (u-r)PL + \sum_{i}^{n} as_i * f(bs(u-r)Q + cs)$$

$$+ \sum_{i}^{n} aw_i * g(bw_i(u-r)Q + cw_i) + d \tag{9}$$

u and y are input and output functions. Q and P are a nonlinear subspace and a linear subspace. L is a linear coefficient. d is output offset. as and aw are a scaling coefficient and a wavelet coefficient. bs and bw are a scaling dilation coefficient and a wavelet dilation coefficient. cs and cw are scaling translation and wavelet translation coefficients. The scaling function f (.) and the wavelet function g(.) are both radial functions, and can be written as equation (10). In system identification process, the wavelet coefficient (a), dilation coefficient (b) and translation coefficient (c) are optimized during learning to obtain the best performance model.

$$f(u) = \exp(-0.5 * u' * u)$$

$$g(u) = (\dim(u) - u' * u) * \exp(-0.5 * u' * u) \tag{10}$$

4. EXPERIMENTAL

The experimental system composes of DC power supplies, one type of commercial inverter with unknown islanding detection, a digital power meter, a digital oscilloscope, resistive (R), inductance (L) and capacitive (C) loads, a AC power system and a computer as shown in Fig 5. In practical of anti-islanding method, some parameters such as grid current/voltage, frequency, impedance and active/reactive power can be chosen for islanding detection up to principle of each technique. In this study, grid current and PCC voltage are selected to be an input and inverter current is selected to be an output of the model. An experimental setup for inverter under islanding condition is designed into three scenarios composed of i) inverter and grid supply energy to load, ii) inverter supply energy to load and grid and iii) inverter supply to RLC resonance load, then the scenarios is performed as shown in Table 2.

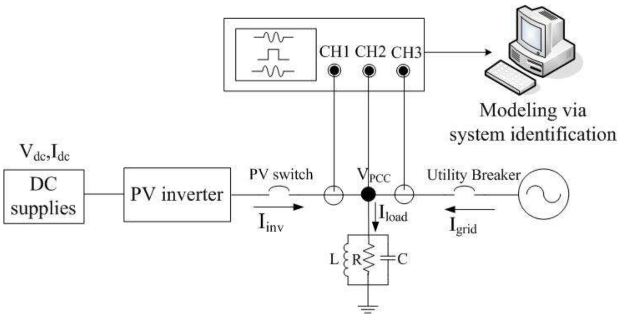

Fig. 5. The experimental setup for anti-islanding modeling.

Table 2. Experiment condition of six scenarios anti-islanding

No	Model input	$P_{inverter}$ (W)	P_{load} (W)	P_{grid} (W)	Load
I	Grid current	1,000	800	-200*	R
II	Grid current	1,200	1,000	200	R
III	Grid current	1,000	1,000	-	RLC
IV	PCC voltage	1,000	800	-200	R
V	PCC voltage	1,200	1,000	200	R
VI	PCC voltage	1,000	1,000	-	RLC

* sign (–) mean grid current energize power into the load

An islanding phenomena of each scenario is done by remove grid current and anti-islanding of inverter is activated as shown in Fig 6-11. The grid current, grid voltage and inverter current are collected by an oscilloscope and transmitted to a computer to calculate power waveforms in single input and single output (SISO) type batch processing of an anti-islanding model.

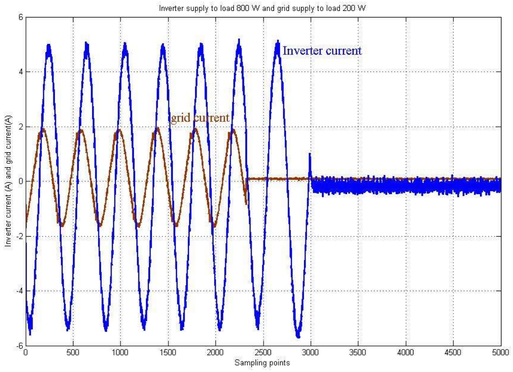

Fig. 6. The input and output of model for Scenario I.

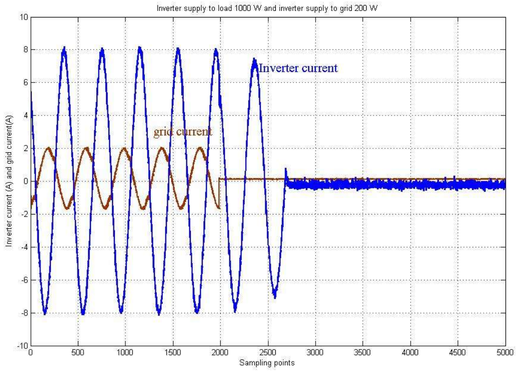

Fig. 7. The input and output of model for Scenario II.

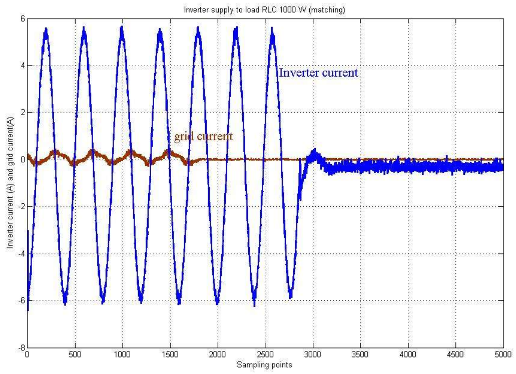

Fig. 8. The input and output of model for Scenario III.

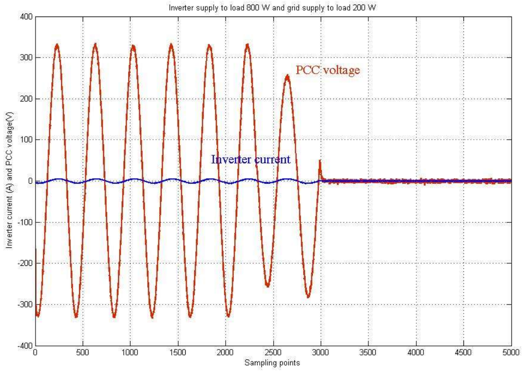

Fig. 9. The Input and output of model for Scenario IV.

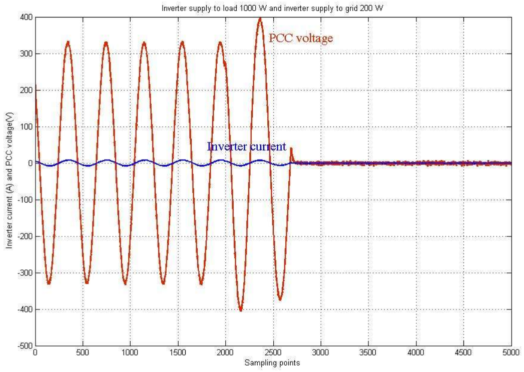

Fig.10 The Input and output of model for Scenario V

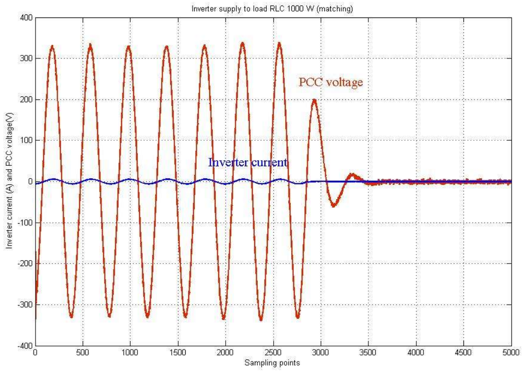

Fig. 11. The Input and output of model for Scenario VI.

In the next step, the input and output of system for islanding study are determined as grid current and inverter current respectively. The collected input and output data is transmitted into the computer program. The data are divided into two groups consist of training data and validating data. Hammerstein-wiener model is chosen for represent the inverter system under islanding phenomena. The computer program is developed by contain the nonlinear model to represent the system. Nonlinear function and linear parameter is selected and output of system is estimated. The implementation of the process has developed by programming using the MATLAB software in order to check accuracy of waveforms and find waveforms of the maximum accuracy compared with actual waveforms [21]. This is executed by adjusting linear pole (n_b), zero plus one (n_f), delay (n_k) and nonlinear estimators. The next process, iterative model waveform and experimented have been validated until the best model performance is derived. The system identification principle is shown in Fig.12.

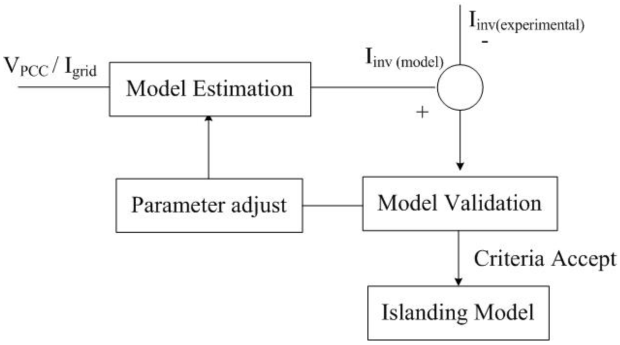

Fig. 12. A system identification principle.

The criteria for model validation are based on quantitative measure of the model quality in terms of model order which should be smallest. The high accuracy which can be calculated from equation (11)

$$Best\ fit = 100 * (1 - norm(y^{*} - y) / norm(y - \bar{y})) \quad (11)$$

where y* is the simulated output, y is the measured output and $\bar{y}$ is the mean of output. FPE is Akaike Final Prediction Error for estimated model which the error calculation is defined as equation (12):

$$FPE = V\left(\frac{1 + d/N}{1 - d/N}\right) \quad (12)$$

where V is the loss function, d is the number of estimated parameters, and N is the number of estimation data. The loss function V is follow in equation (13) where θ_N represents the estimated parameters.

$$V = \det\left(\frac{1}{N}\sum_{1}^{N} \varepsilon(t,\theta_N)(\varepsilon(t,\theta_N))^{T}\right) \quad (13)$$

The Akaike Information Criterion (AIC) as shown in equation (14) is used to calculate a relative comparison of models with different structures. A FPE and AIC should be smallest for a an effective model.

$$AIC = \log\ V + \frac{2d}{N} \tag{14}$$

5. RESULT AND DISCUSSION

The inverter models under islanding condition in six scenarios are estimated until suitable model is obtained. Table 3 shows the model properties of inverter anti-islanding in scenarios I. This scenario grid current as input of model and inverter supply energy to resistive load 800 W and grid 200 W. The best accuracy of model is obtained by nonlinear I/O sigmoid network estimator with linear parameters 2, 7 and 3, percentage of accuracy 82.30, FPE 0.69 and AIC -0.49 respectively.

Table 3. Model properties of inverter anti-islanding in scenario I

Nonlinear	Linear parameter			Model Properties		
I/O	b_n	f_n	n_k	% fit	FPE	AIC
DZ	5	4	4	71.37	1.59	0.46
ST	5	4	1	79.20	1.97	0.64
PW	3	3	2	72.40	0.93	0.06
SN	2	7	3	82.30	0.69	-0.49
WN	3	4	3	62.17	0.78	-0.54

Table 3 shows the model properties of inverter anti-islanding in scenarios VI. This scenario PCC voltage as input of model and inverter supply energy to RLC resonant load 1000 W. The best accuracy of model is obtained by nonlinear I/O wavelet network estimator with linear parameters 1, 1 and 1, fit 83.62, FPE 0.24 and AIC -1.39.

Table 4. Model properties of inverter anti-islanding in scenario VI

Nonlinear	Linear parameter			Model Properties		
I/O	nb	nf	nk	% fit	FPE	AIC
DZ	1	1	2	80.10	0.35	-1.03
ST	4	5	3	86.27	0.38	-0.95
PW	1	1	1	84.20	0.33	-1.1
SN	1	1	1	83.48	0.24	-1.41
WN	1	1	1	83.62	0.24	-1.39

The rest scenarios are done in the same manner of scenario I and VI. The best model properties of each anti-islanding for six scenarios are shown in Table 5.

In Fig.13-14 shows a comparison of inverter current ac from modeling and experimental of the best model from scenarios I and IV.

The model analysis of inverter under islanding condition can be described by nonlinear properties and linear properties of system. The nonlinear properties of input and output estimator for sigmoid network estimator of scenario I and wavelet network of scenario IV follow as Table 6 and Table 7 respectively.

Table 5. Model properties for anti-islanding of six scenarios

No	Nonlinear	Linear			Model Properties		
	I/O	b_n	f_n	n_k	% fit	FPE	AIC
I	SN	2	7	3	72.70	1.08	0.07
II	SN	1	2	1	76.52	0.43	-0.83
III	SN	1	5	3	83.86	0.24	-1.38
IV	WN	1	1	1	87.64	0.23	-1.44
V	WN	1	1	1	85.85	0.18	-1.68
VI	WN	1	1	1	83.62	0.24	-1.39

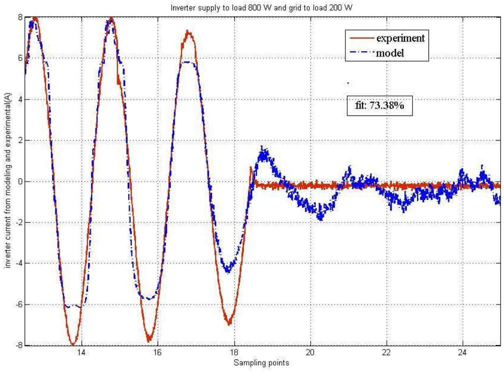

Fig. 13. A comparison model and experiment of scenario I.

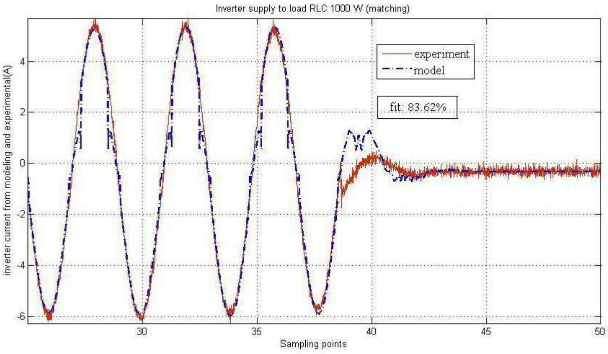

Fig. 14. A comparison model and experiment of scenario VI.

Table 6. The Properties of Sigmoid network estimators

Properties	Input nonlinear	Output nonlinear
RegressorMean	0.0052	-9.61×10^{-17}
NonLinearSubspace	1	1
LinearSubspace	1	1
LinearCoef	-0.1387	-6.1046
Dilation	[1x10 double*]	[1x10 double]
Translation	[1x10 double]	[1x10 double]
OutputCoef	[10x1 double]	[10x1 double]
OutputOffset	-0.0527	1.1208

* double is type of data structure.

Table 7. The properties of wavelet network estimators

Properties	Input nonlinear	Output nonlinear
Number of Unit	6	11
RegressorMean	-8.5126	-98.55
NonLinearSubspace	0.0056	4.5818e-004
LinearSubspace	0.0056	4.5818e-004
OutputOffset	-7.0973	-0.4855
LinearCoef	176.51	3.1140
ScalingCoef	[0x1 double*]	[3x1 double]
WaveletCoef	[6x1 double]	[8x1 double]
ScalingDilation	[0x1 double]	[3x1 double]
WaveletDilation	[6x1 double]	[8x1 double]
ScalingTranslation:	[0x1 double]	[3x1 double]
WaveletTranslation	[6x1 double]	[8x1 double]

* double is type of data structure.

Linear system analysis is concerned with the study of equilibrium and change in dynamical systems, containing the variables may change with time. The variables include system inputs (grid current or PCC voltage) and outputs (inverter current) as well as variables describing internal states of the system. However, in order for linear system analysis to be applicable, the model must posses the linear property. The linearization technique is help us to approximated nonlinear system to be a linear time invariant (LTI) system by considers a limit range value around an operating point. The example of mathematical model from inverter under islanding model in scenario I is illustrated follow as discrete time model, state-space equation, transfer function and zero-pole gain equation.

i) Discrete-time polynomial model

The input-output polynomial model written in equation (15) represents the relationship between input, output and disturbance or error with their coefficients. The polynomials B and F contain the time-shift operator q which equivalent to z of Z-transform.

$$y(t) = \left[\frac{B(q)}{F(q)}\right] u(t) + e(t) \qquad (15)$$

$$B(q) = -0.001059q^{-1} + 0.001263q^{-2}$$

$$F(q) = 1 - 1.8q^{-1} - 0.2q^{-2} + 1.1q^{-3} + 1.1q^{-4} - 0.2q^{-5} - 1.8q^{-6} + 0.9q^{-7}$$

ii) Discrete time state space equation

The state of system is explicitly accounted for by an equation known as the state equation. The system output is given in terms of combination of current system state and the current system input through the output equation. The two equations from system of equations are known as state space equation. For consider as LTI system, matrices will be time invariant and time variable is discrete which indicated as (k). The state space equation of the discrete signal is follow as equation (16)

$$\begin{aligned} x(k+1) &= A(k)x(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \qquad (16)$$

$$A = \begin{bmatrix} 1.89 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0.23 & 0 & 1 & 0 & 0 & 0 & 0 \\ -1.12 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1.12 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0.22 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1.87 & 0 & 0 & 0 & 0 & 0 & 1 \\ -0.98 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} -0.001 & 0 \\ -0.001 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \qquad \mathrm{D}\begin{bmatrix} 0 & 1.256 \end{bmatrix}$$

iii) Transfer function

A transfer function also known as the network function is a mathematical representation, in terms of spatial or temporal frequency of the relation between input and output of LTI system. For this system transfer function is written in equation (17)

$$H(z) = \frac{num(z)}{den(z)} = \qquad (17)$$

$$\frac{-0.001059z^{6} + 0.001263z^{5}}{z^{7} - 1.89z^{6} - 0.23z^{5} + 1.12z^{4} + 1.12z^{3} - 0.22z^{2} - 1.87z + 0.98}$$

iv) Zero-Pole-Gain (ZPK) equation

Zero pole gain is another from of transfer function where z presents the zeros, P are the poles and K are the gain of transfer function. The number of poles must be greater than or equal to the number of zeros, if the poles and zeros are complex, they must be complex-conjugate pairs. The ZPK equation is written in equation (18)

$$H(z) = K\frac{Z(z)}{P(z)} = \qquad (18)$$

$$\frac{-0.0010587\mathrm{z}^{3}\,(\mathrm{z}-1.193)\,(\mathrm{z}-2.545\mathrm{e}-008)\,(\mathrm{z}+2.545\mathrm{e}-008)}{(\mathrm{z}+0.99)\,(\mathrm{z}^{2}-1.99\mathrm{z}+0.99)\,(\mathrm{z}^{2}-1.9\mathrm{z}+0.99)\,(\mathrm{z}^{3}+1.07\mathrm{z}+0.99)}$$

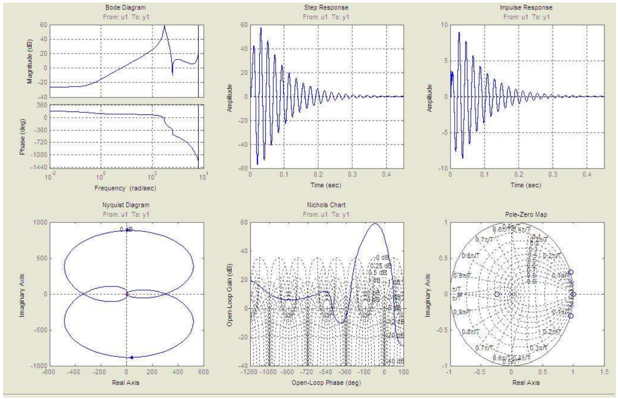

Fig. 7. A Graphical tool for linear system analysis.

In addition, the graphical tool for system analysis such as Bode plot, step response, impulse response, frequency response, Nyquist plot, Nicole chart and zero-pole gain can be illustrated as shown in Fig 8. These graphical tools can be used to design the linear controller, stability analysis, causality, system response analysis and signal processing.

6. CONCLUSION

This paper proposes islanding protection modeling of distributed generator in order to study the anti-islanding behavior from mathematical model and also utilization in model based control system. The islanding phenomenon is simulated and anti-islanding scheme has been operated. The waveform of grid current and PCC voltage as input of model and inverter current as output of model have been collected for system identification processing. The three case of experimental condition from adjust power management have been experimented follow as i) inverter supply energy to resistive load and grid, ii) inverter and grid supply to load and iii) inverter supply to RLC resonance load. The totally six scenarios is performed and their anti-islanding modeling is derived. The suitable model for represent the anti-islanding is extracted by model using grid current as input in scenarios I-III obtaining high effective model from nonlinear model containing a sigmoid network and the most effective model using PCC voltage as input in scenarios IV-VI are derived from of wavelet network. The derived mathematical model of inverter under islanding is analyzed by nonlinear properties and linear properties which are helpful for understand anti-islanding phenomena, islanding detection techniques, and model based prediction control for islanding in the future work. Nevertheless, in this paper, only one case of unknown islanding detection is implemented. In practical, the various type of anti-islanding should be model in order to make a comprehensive the islanding strategy in order to increase the efficiency of islanding detection techniques modeling.

ACKNOWLEDGMENT

The authors would like to thanks Energy Policy and Plan Office (EPPO) Ministry of Energy and Rajamangala University of Technology Lanna for support research funds.

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