A Hybrid Islanding Detection Method For Distribution Systems

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ABSTRACT

Continuous operation of Renewable Energy Systems (RES) is achieved either in grid-connected mode or in autonomous mode in the form of Islands or Microgrid, which has predefined boundaries. Thus, distribution systems should be capable of detecting islanding condition for smooth transition to an Islanded mode. In this article, a hybrid islanding detection method, which combines remote and passive methods, is proposed. Distributed Generation (DG) units can be in the form of inverter interfaced or synchronous based generators and when used together can cause difficulti¥es in islanding detection such as delay or inaccurate detection. The number of DG units in the network also affects the accuracy of islanding detection. Thus a new hybrid method, which is based on communication and passive methods, is proposed to overcome this problem. The accuracy and effectiveness of the proposed hybrid method is investigated using PSCAD software. The proposed detection method features an improvement in detection accuracy.

Keywords: Islanding detection, communication method, distributed generation, distribution system, hybrid method, micro grid, passive methods.

INTRODUCTION

In recent decades, due to market liberalization and environmental regulations, the number of DG units commissioned in distribution systems has increased around the world. Islanding of DG unit occurs when a section of the distribution system is electrically isolated from the rest

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of grid; whereas, the DG unit continues to supply loads in the separated area. According to the IEEE 1547 *Std*., islanding should be detected and isolated within 2 seconds [1].

Islanding can be classified as unintentional islanding and intentional islanding [2, 3]. Once unintentional islanding takes place, distribution networks will be separated into several isolated parts. Each part may involve loads, generation or both generation and load. Islanding can change the network topology. Once the islanding occurs, regulated busbar could be considered as a slack busbar and variation in voltage and frequency could affect the stability and may lead to voltage collapse at all feeders in the islanded area. Hence, unintentional islanding should be detected by IDMs within a very short interval. On the other hand, in intentional islanding, an autonomous system can be energized by DG unit and customers could be supplied at any emergency conditions. Intentional or planned islanding will increase the power supply quality, reduce fault level currents and customer's outage [2,4]. Due to these problems, many researches have been undertaken to promote islanding in distribution networks. For both types of islanding, all DG units should be visible to the system operator and they should be equipped with IDMs. Figure 1 shows a synchronous based DG connected to the distribution network. After grid disconnection via circuit breaker, the DG unit can energize rest of the network. Monitoring of parameters such as voltage, frequency and harmonics at the Point of Common Coupling (PCC) is the main philosophy of islanding detection [5].

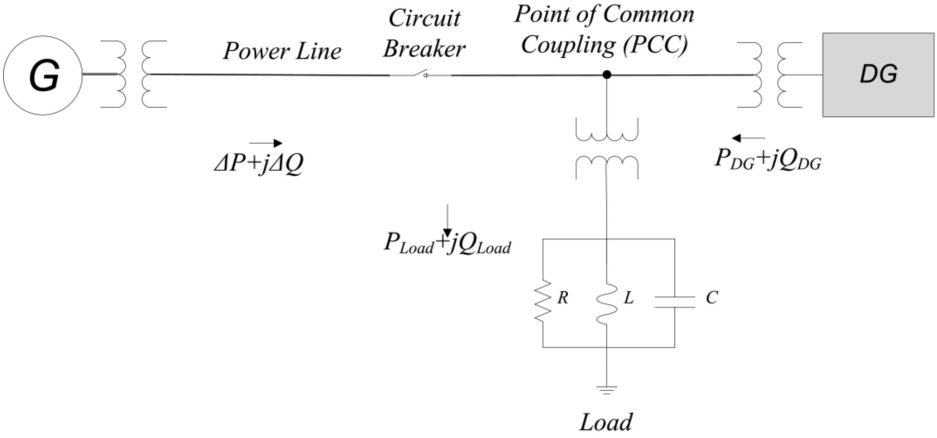


Figure 1. Power system with DG connected at PCC.

In Figure 1, $\Delta P = P_{Load} - P_{DG}$ and $\Delta Q = Q_{Load} - Q_{DG}$. When $\Delta P = 0$ and $\Delta Q = 0$, islanding could be formed. Whenever $P_{Load} = P_{DG}$ and $Q_{Load} = Q_{DG}$, it shows an equilibrium point in the network. In this case, the variation of the PCC voltage and frequency remain in the acceptable range and islanding cannot simply be detected. This area is known as none-detection zone (NDZ) [6,7]. Several IDMs have been developed to address this problem including:

a) Passive detection (PDM)
b) Active detection (ADM)
c) Communication Based detection methods (CDM).

Passive method is a type of IDM which includes; Phase Jump Detection (PJD) method, Over/Under Voltage Monitoring, Over/Under Frequency monitoring, Rate Of Change of Voltage (ROCOV), Rate of Change of Frequency (ROCOF), Rate of Change of Frequency Over Power (ROCOFOP), Rate of Change of Output Power (ROCOP), Zero-Sequency Impedance based on Wavelet, Reverse VAR Detection, Voltage Harmonic or TDH monitoring and Vector Shift (VS) [8-12]. Generally, passive methods are fast enough for islanding detection. Nevertheless, when the mismatch between generation and load is small and does not lead to significant change in network parameters, passive methods have a large NDZ. The time detection performances show good agreement with IEEE standards for passive methods.

Active detection methods have been developed to decrease the NDZ. Mostly, these methods are based on perturbation and observation at PCC point. Active methods affect the PCC by distorting voltage or frequency. The PCC voltage or frequency cannot be varied too much due to the stiff power supply by grid. However, voltage and frequency distribution could violate the limits during islanding condition. Active methods are able to detect the islanding phenomenon during the load and generation balance condition. However, the most important disadvantage of the active detection method is that, the simultaneous operation of different types of DG units with different active methods introduces various high disturbance into the system Active Frequency Drift (AFD), Adaptive Logic Phase shift (ALPS), Voltage Positive Feedback and slip mode frequency shift are categorized as active methods [12-22].

Communication based methods are the most reliable methods. Theoretically, communication based method is the most accurate method. On the other hand, they suffer from nuisance tripping. As long as the signal detector (SD) senses the generated signal from signal generator (SG), DG unit is considered as grid connected. Once islanding takes place or any switch operation causes lost communication between the SG and SD, islanding will be detected. In comparison to active methods, Power Line Signaling (PLS) sends one signal to down-stream DG units through the transmission line to detect the islanding. By implementation of PLS, the signal interface caused by different active methods is solved. The weakness of this method is the high cost of installation and its sensitivity to noise [14, 23-28].

In general, Hybrid Detection Methods (HDM) combine the features of aforementioned techniques to increase the detection accuracy. The HDMs are developed in order to overcome drawbacks of local and Remote Detection Methods and improve their performance. From this point, architecture of two local based HDM consists of one passive method as a primary detection method and one active method as secondary detection method. In fact, just when the passive detection method detects a suspected unintentional islanding situation, Active Detection Method starts to function and perturbs the point of common coupling to detect the islanding. Hence, injected distortion by Active Detection Method is considerably reduced

In this article, to overcome the shortcomings of individual methods, a hybrid method, which is a combination of communication method and several passive methods, is proposed. The proposed method is using the power system to send islanding detection signals and passive method is utilized to extract these islanding detection signals at the DG unite terminal.

PROPOSED HYBRID DETECTION METHOD

As discussed in the previous section, islanding should be detected within 2 sec. The communication method, which was developed by Xu. Wilson is highly reliable and capable of detecting the islanding within acceptable time [26,27]. Figure 2 illustrates the placement of the signal generator (SG) and signal detector (SD) in the network. The PLS method uses the distribution network to send the islanding detection signals to all downstream DG units. If the SD (receiver) receives the signals, then the DG is connected to the grid. Losing certain number of islanding signals indicates that the connection between DG unit and grid is lost and islanding has formed. The most expensive part of the PLS equipment is the signal generator and signal transformer. Any reduction in the size of this equipment will lead to decrease in costs. Due to the damping feature of the power network, signal detector should be capable of detecting the weak signals at any situation in the system.

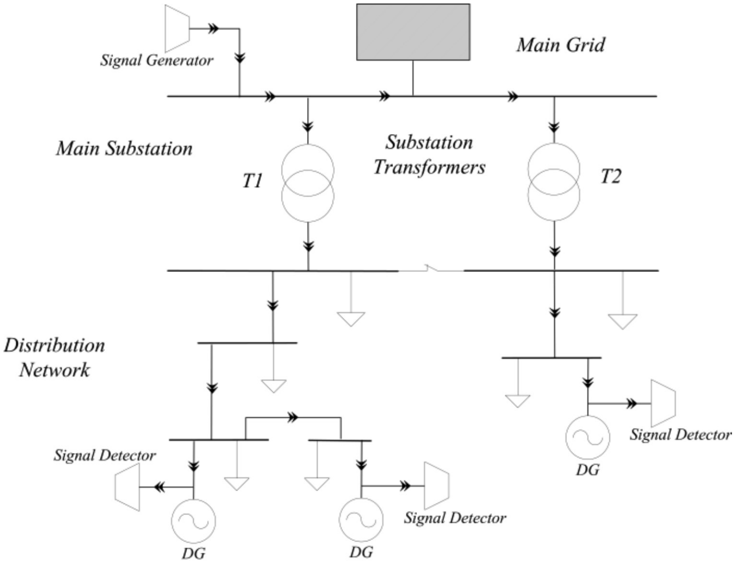
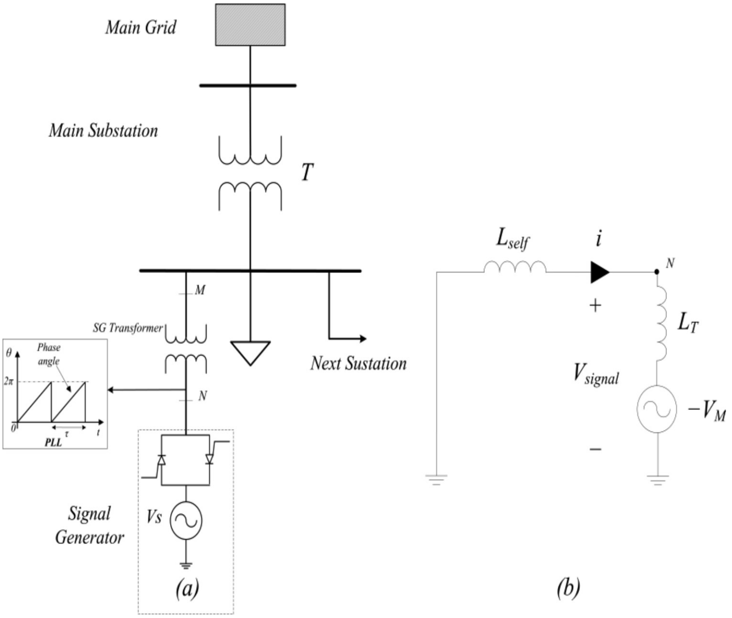


Figure 2. Schematic diagram of the distribution network and location of signal generator and signal detectors.

Signal Generator

Signal generator is used to generate the islanding detection signals. As seen in Figure 3, SG is connected at the main substation via a step up transformer. The signal generator can be connected t between one phase (for example phase *a*) and ground ore between two phases. Due to power quality concerns, phase to ground channel has been chosen to send the signals. The Islanding Detection Signals (IDSs) are created by triggering the thyristors at certain voltage every 3 cycle of the main voltage waveform [26,27].

Thyristors are triggered at several degrees before zero crossing point of the voltage waveform. If firing of thyristors be performed when voltage angle is $\pm\pi/2$, strength of the islanding signal will be maximized. However, increasing the signal strength will lead to degraded power quality. From this point, a phase locked loop (PLL) is utilized to detect



(a) (b)

Figure 3. (a) SG connections to main substation. (b) Signal generator model.

the voltage angle at main substation. When thyristors are triggered, voltage at drops to zero. The voltage waveform will be distorted during the triggering time as show in Figure 4. This disturbance is considered as an islanding detection signal in every 3 cycle. The strength of the IDS is directly related to the triggering angle and duration of the switching.

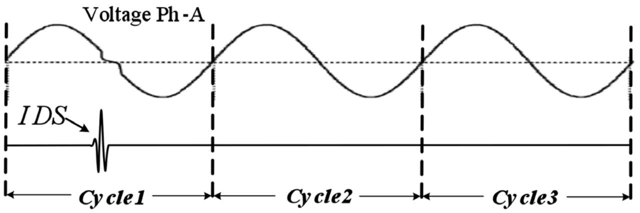


Figure 4: Distorted terminal voltage and the IDS voltage in each three cycle

Voltage and signal strength can be written as Equations (1) and (2) respectively [16]:

$$V_M(t) = -\sqrt{\frac{2}{3}} \cdot U_L \sin(\omega t) \tag{1}$$

$$V_{Signal} = \sqrt{\frac{2}{3}} \cdot U_L \cdot \frac{L_{self}}{L_{self} + L_T} \sin(\omega t) \tag{2}$$

where L_{self} and L_T represent self-inductance of the grid and SG transformer inductance respectively. In order to define the strength of the IDS, k, ratio of its peak value to the peak of its carrier is used [26, 27]. Equation (3) presents a factor that is used to identify the IDS strength. The more strong IDS, the higher value for *k*. Since injecting strong IDSs cause power quality problems, the strength of the injected IDSs should be maintain as low as possible. However, weak signals may not be extractable at the DG site.

$$k = \frac{V_{Signal-peak}}{V_{PG-peak}} = \frac{L_{self} \sin\delta}{L_{self} + L_T} = \frac{X_{self} \sin\delta}{X_{self} + X_T} \times 100\% \tag{3}$$

Three different detection techniques are proposed to extract the islanding signals in the next sections.

SIGNAL DETECTOR (RECEIVER)

Several methods have been developed to extract the IDSs, such as comparing the received signal with a reference signal, monitoring of harmonics and digital signal processing methods. The receiver reveals the islanding phenomenon by monitoring the presence of IDSs. In Figure 5, the configuration of the signal detector is illustrated. As seen in this figure, the signal detector consists of two parts. The first part is "Islanding Signal Extractor" and the second part is "Lost Islanding Signal Counter" which activates the islanding alarm when 4 consecutive IDSs are lost. As mentioned previously, no reception of the IDSs is considered as islanding. However, several contingencies such as faults and circuit breaker malfunctioning will lead to loss of some IDSs. Hence, in order to differentiate between temporary contingencies, non-detection of 4 consecutive IDSs is considered as islanding phenomenon.

Three different method for IDS extraction are presented in this article:

Phase jump extraction;
d-q frame extraction;
Frequency monitoring extraction.

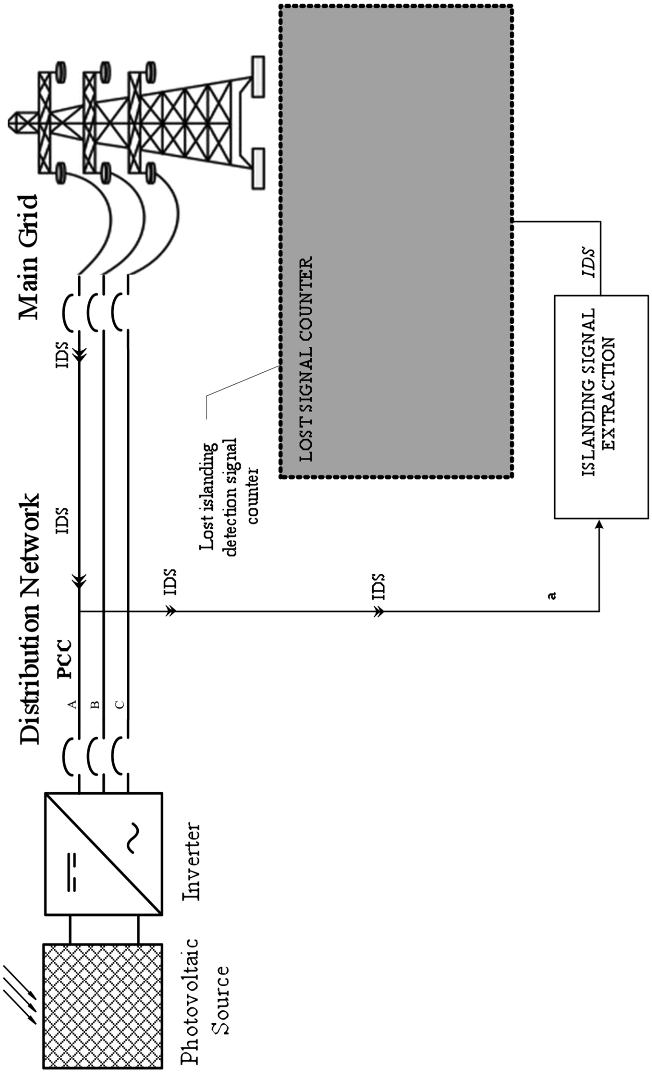


Figure 5: Signal detector configuration.

Phase Jump Extraction

Period and frequency are detected by monitoring the voltage waveform. During zero crossing of the normal operation, τ = τ′. However, as shown in Figure 6, at islanding point, period of voltage (τ) will be changed to a new value (τ′) where $\Delta\tau = \tau - \tau' \neq 0$.

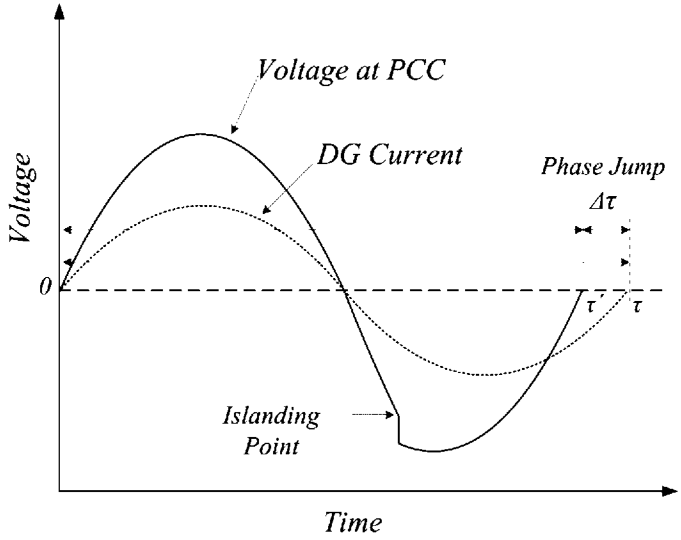


Figure 6. Sudden change in PCC voltage angle.

Figure 6 shows the voltage phase jump for one islanding detection signal. Any change in Δτ indicates the change in the phase of voltage at PCC. Figure 7 describes the procedure of the phase jump method. Frequency of the voltage at PCC is measured via the first block in Figure 5.

In the next two parts, if any unacceptable differences between τ and τ′ ($\Delta\tau \neq 0$) is observed, islanding can be detected and the control signal will be sent to the DG circuit breaker. During normal operating conditions, the voltage phase angle of the grid and load are synchronous. However, when the islanding signal reaches to the PCC, it changes the phase angle θ which can be detected by PLL. Equation (4) describes transform from *d-q* frame α–β frame.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{4}$$

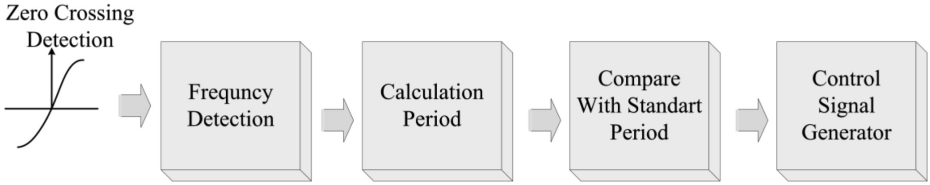


Figure 7. PJD method with zero crossing detection.

Figure 8 shows the PLL to generate the reference waveform at the main frequency of the system. As shown previously in Figure 6, once IDS reaches to the receiver, the phase voltage angle at PCC will change rapidly. In this technique, the phase angle of the generated reference waveform is compared with the carrier waveform to extract the islanding detection signals.

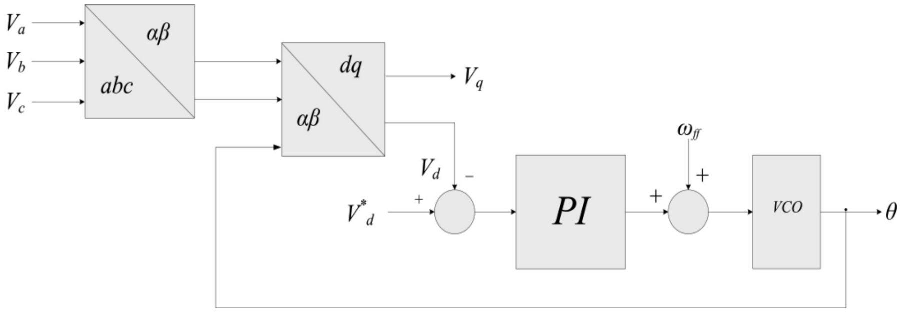


Figure 8. Phase detection using PLL.

Figure 9 illustrates the control system to produce the reference waveform using PI controller. First, the voltage angle (θ) at PCC will be detected by the PLL. This angle is used to create the sinusoidal pattern.

Figure 10 illustrates the flowchart of signal extraction by using PLL. The detected voltage phase angle (θ) via PLL is used to generate a reference waveform (V_{ref}). This reference waveform is compared with the voltage waveform, which carries the signal. Once islanding occurs, the angle of voltage phase *a* (V_{ph}) shifts to a new value.

About this shift, as the carrier waveform and reference waveform are synchronized, islanding detection signals can be extracted.

The *d-q* Frame Extraction

The *d-q* frame is used to improve the detection accuracy. The volt-

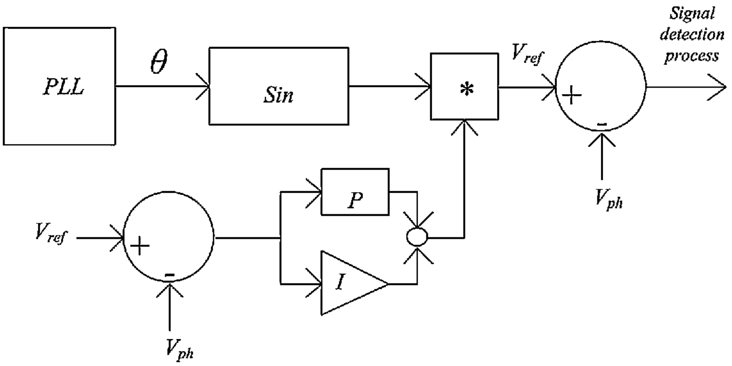


Figure 9. Generation of reference waveform to compare with phase voltage.

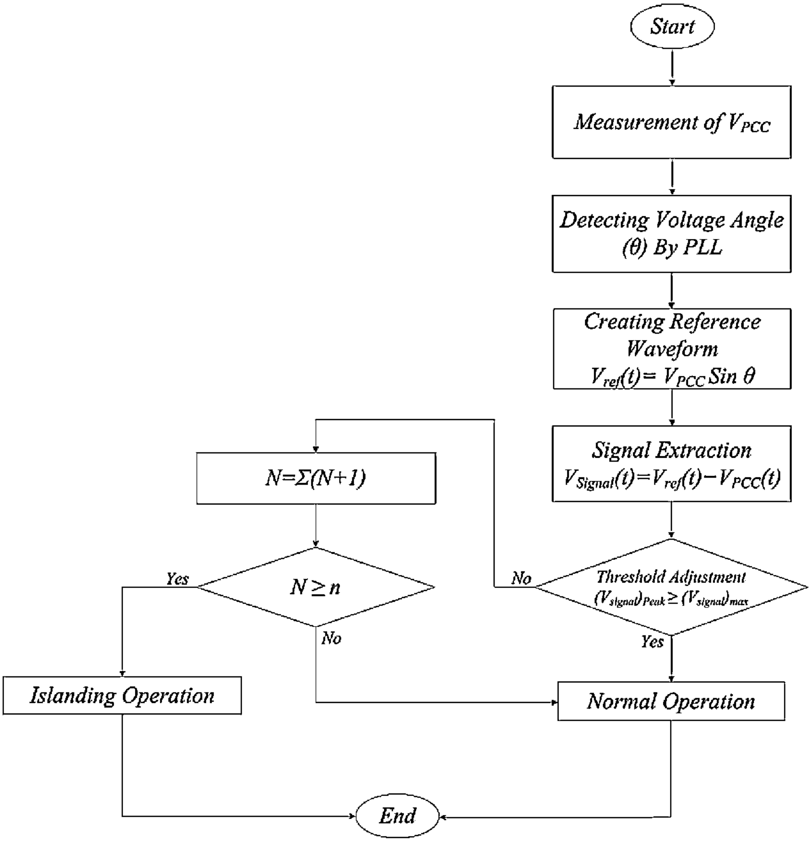


Figure 10. Islanding detection using created pattern.

age phase angle (θ) at PCC is used in combination with Park's Transform to calculate V_d and V_q. Hence, very weak signals can also be extracted via *d*-*q* frame monitoring. Figure 11 shows the flowchart using the *d*-*q* frame. By monitoring the phase angle, islanding can be detected.

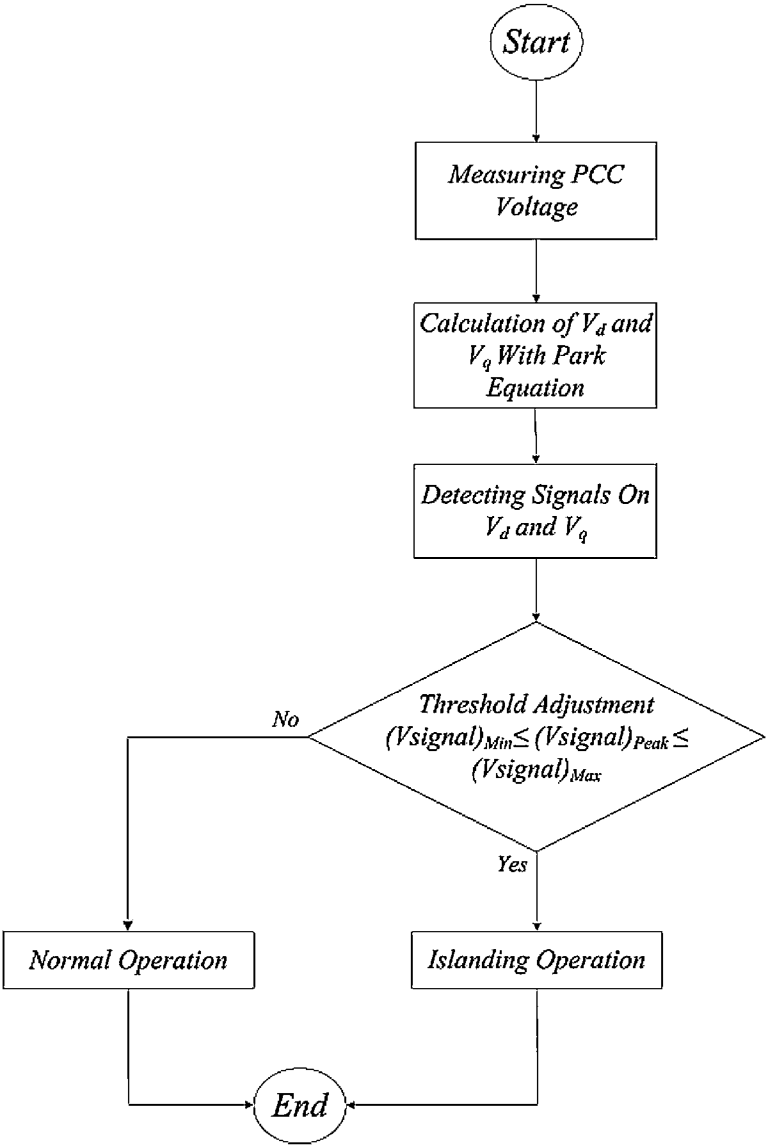


Figure 11. Flowchart shows the PLS-PJD-*d*-*q* signal extraction.

The θ(*t*) represents an instantaneous phase angle. Hence, Δθ(*t*) can be defined as follows (where $0^\circ \le \theta \le 360^\circ$, $t \ge \tau$):

$$\Delta\theta(t) = \theta(t-\tau) - \theta(t) \tag{5}$$

If $\Delta\theta(t) \neq 0$, Vq will have a magnitude. The *d*-*q* frame detects the islanding for various load conditions. Changes in V_q are used to extract the islanding signals. Figure 12 illustrates the *d*-*q* detection method. As shown in Figure 15, the system voltage angle (θ) is detected by PLL block. In the next step, V_d and V_q are calculated by using Park's Transform.

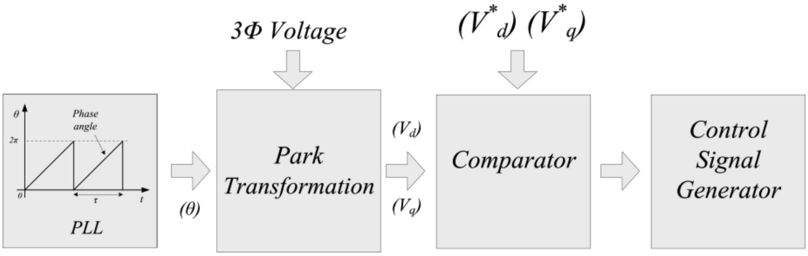


Figure 12. Schematic diagram for *d-q* IDM with PLL for angle detection.

Frequency Monitoring Extraction

The frequency of the generated islanding signals can be observed at the PCC. For this reason, frequency changes will indicate the islanding detection signals. Load and generation changes have destructive impact on the extraction of the islanding signals. Setting the threshold for the frequency is very difficult due to these variations and may lead to wrong detection. Frequency variations should be omitted to overcome this problem. Hence, it is proposed to use a delay in islanding extraction loop to omit the variations. The IDS extraction procedure using the frequency is shown in Figure 13.

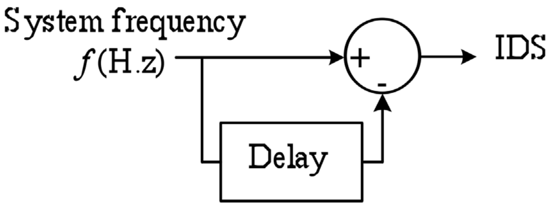


Figure 13. Extracting the IDS using frequency of the system

RESULTS AND DISCUSION

Generic Test Distribution System

In order to investigate the proposed islanding detection method a modified 11 kV, 50 Hz generic network from Malaysian electrical distribution utility is modeled using EMTDC/PSCAD. The single line diagram of this network is presented in Figure 17. Both transformers in the main substation are 132/11 kV, Δ-Yg, rated at 30 MVA and impedance 10%. Fault level at 132 kV busbar is 14 kA and 17.8 kA at 11 kV. A 2 MW synchronous generators were used as a DG units.

Figure 14 represents a practical network, which is used to analyze and verify the proposed methods. The main substation transformers have the voltage ratio of 33 kV/11 kV. The 1 MW, 50 Hz distributed generator is connected to feeder 8. Islanding is initiated by opening the feeders' circuit breakers. Three different case studies are investigated to determine the islanding detection capability of each IDM.

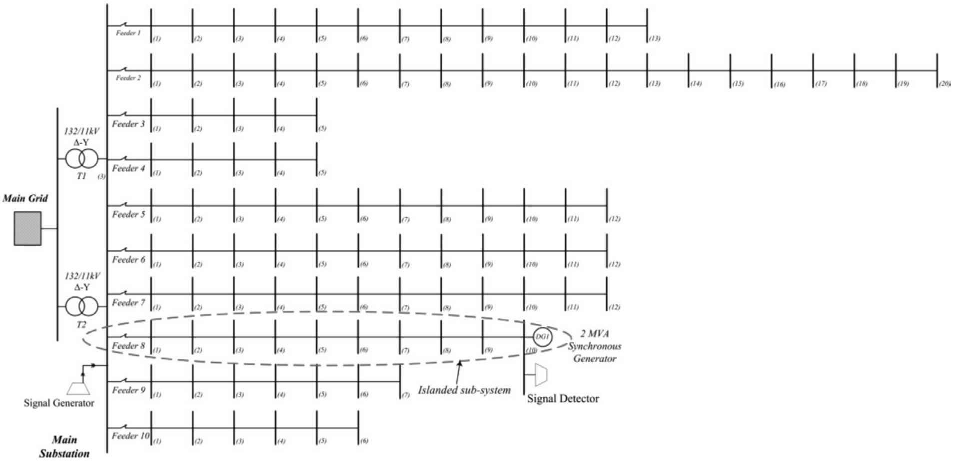


Figure 14. Practical test network with signal generator and signal detector.

Load Profile

For the first case study, 24-hour load pattern at main substation is used. Active and reactive power changes for 24 h at main feeder are shown in Figure 18. Minimum and maximum active and reactive powers for each feeder during 24 h are shown in Table 1.

Table 1. Minimum and maximum load on each feeder.

Feeder No.	Active Power (MW)		Reactive power (MVAR)	
	P_{min}	P_{max}	Q_{min}	Q_{max}
Feeder 1	0.462	0.571	0.233	0.329
Feeder 2	0.707	1.15	0.502	0.562
Feeder 3	0.178	0.294	0.086	0.142
Feeder 4	0.178	0.294	0.086	0.142
Feeder 5	0.426	0.701	0.206	0.338
Feeder 6	0.426	0.695	0.206	0.336
Feeder 7	0.427	0.623	0.207	0.305
Feeder 8	0.391	0.571	0.198	0.312
Feeder 9	0.249	0.363	0.12	0.177
Feeder 10	0.213	0.351	0.103	0.152

This case study investigates the impact of practical load pattern on islanding detection accuracy and speed. With reference to Figure 15, load changes during the 24 hours.

Injected Islanding Detection Signals

Islanding detection signals are injected in the main substation. As explained in the previous section, IDSs are injected between phase *a* and ground channel. Figure 16 presents the voltage wave form of the phase *a* at the main substation. As seen in this Figure, the IDS is injected near to the zero crossing point of the voltage wave form.

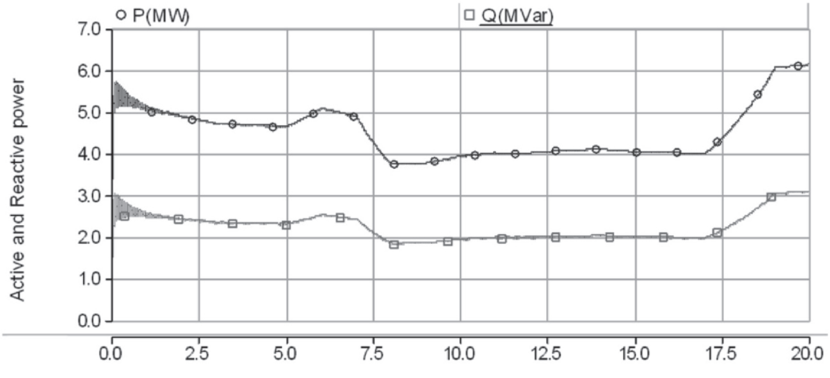


Figure 15. Load pattern at the main substation transformers.

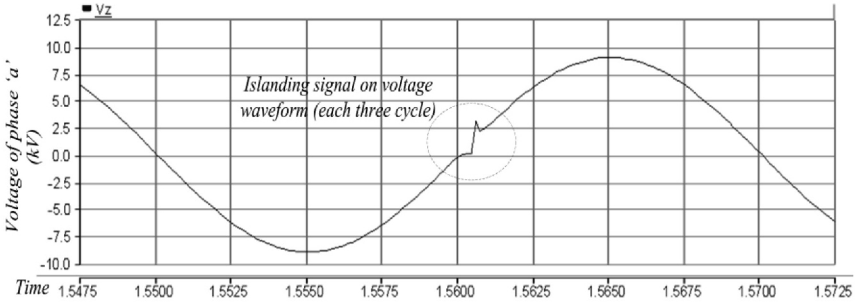
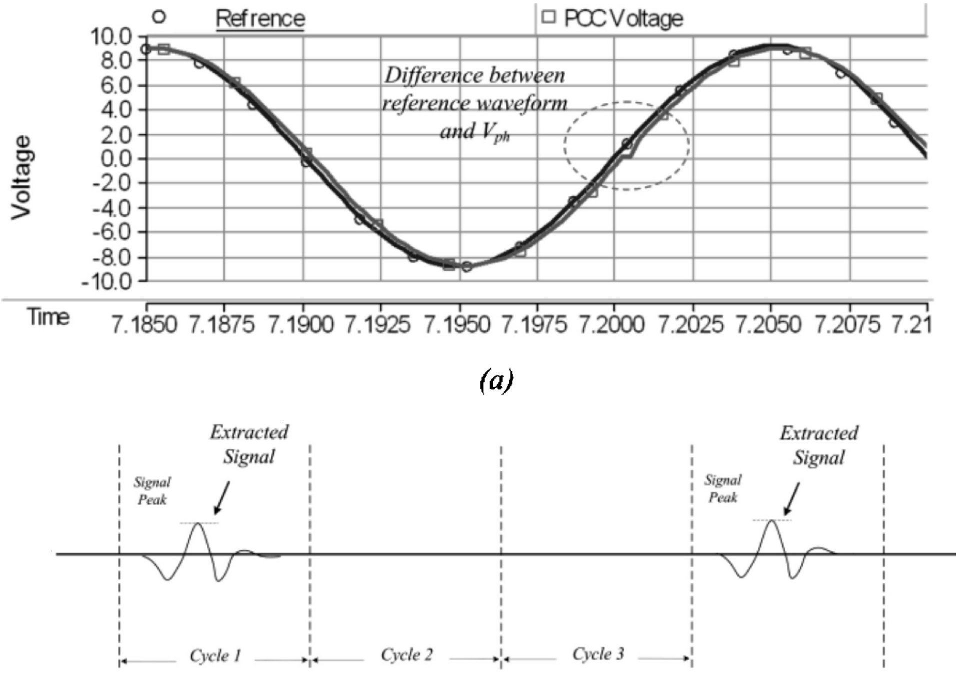


Figure 16. Signal strength in the main substation at 11kV busbar.

Extracting IDSs Using Phase Jump Detection

Figures 17(a) and 17(b) illustrates the two waveforms and extracted signals. The peak value of the signal $(V_{signal})_{\text{peak}}$ has been used to adjust the thresholds. As long as the reference waveform is similar to the measured phase voltage, the received signal will be extracted. PI controller



(a)

(b)

Figure 17. (a) Reference pattern using the PLL. (b) Extracted IDS.

is used to reduce the difference between two waveforms.

The PLL should not track the voltage waveform very fast, because the fast tracking decreases the magnitude of the extracted islanding detection signal. In contrary, slow PLL will cause considerable differences between generated reference and main waveform. Thus, magnitude of extracted islanding signal in this technique depends on the PLL settings.

Extracting IDSs Using *d-q* Frame

Figure 18 shows the simulated V_q with the superimposed signal from the signal generator. Even under perfect match between load and generation in the separated part, islanding is detectable using this hybrid method. As seen in the Figure 18, IDSs are disappeared after islanding. Since temporary faults may cause some of the IDSs get lost, losing 4 consecutive IDSs is considered as islanding phenomenon to prevent wrong islanding detection.

Extracting IDSs Using Frequency Monitoring

Figure 19 shows the islanding detection signals carried by frequency. As seen in this figure, measuring the frequency reveals the existence of the IDSs. However, load and generating variation has destructive impact on islanding signals.

To remove these negative impacts of load/generation variations on IDSs, small delay is applied on detection process as showed in Figure13. Figure 20 shows the extracted islanding signals after removing variation. As seen in Figure 20, the IDSs are extractable during generation variation and the effect of frequency is removed at 4 sec. Similar to the previous extraction methods, when 4 continues missed islanding detection signals considered as islanding phenomenon.

CONCLUSIONS

The proposed method is employed in the signal detector (receiver) to extract the islanding detection signals. As showed in the results, the proposed method were capable of accurate extracting of the islanding detection signals. The proposed islanding detection method utilizes the voltage phase jump to extract the islanding detection signals. The proposed detection method is capable of extracting the weaker islanding detection signals compared to the existing methods.

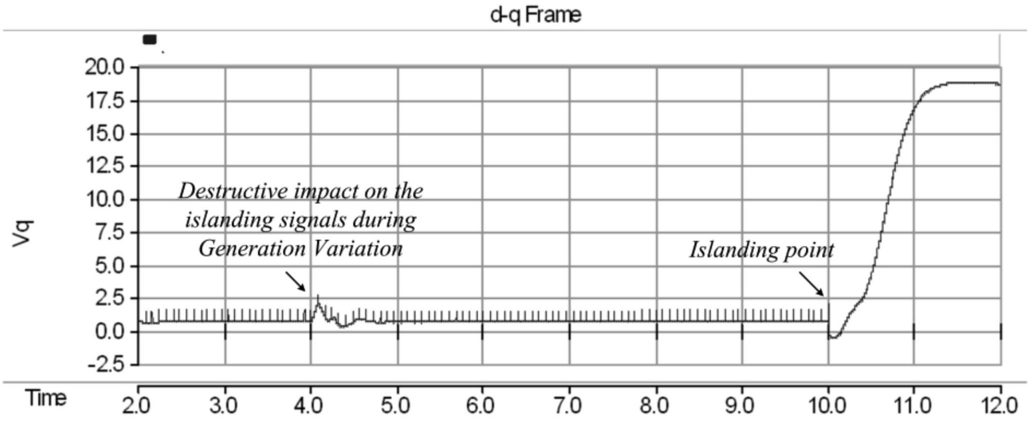


Figure 18. Islanding detection signals using *d-q* frame.

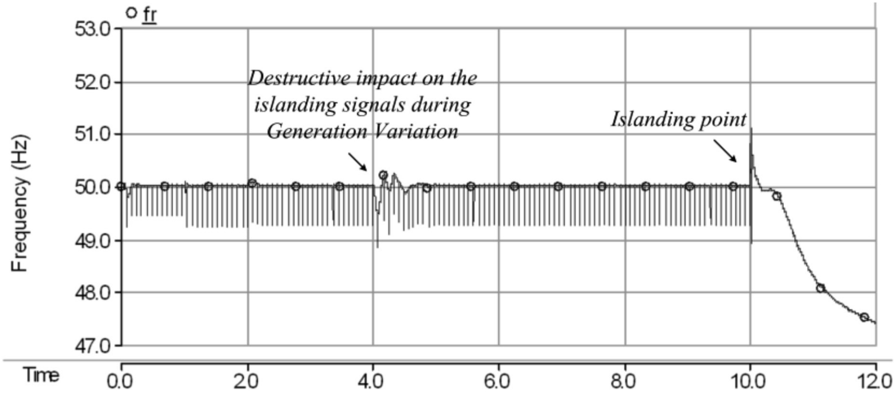


Figure 19. Islanding signals on *Vq*

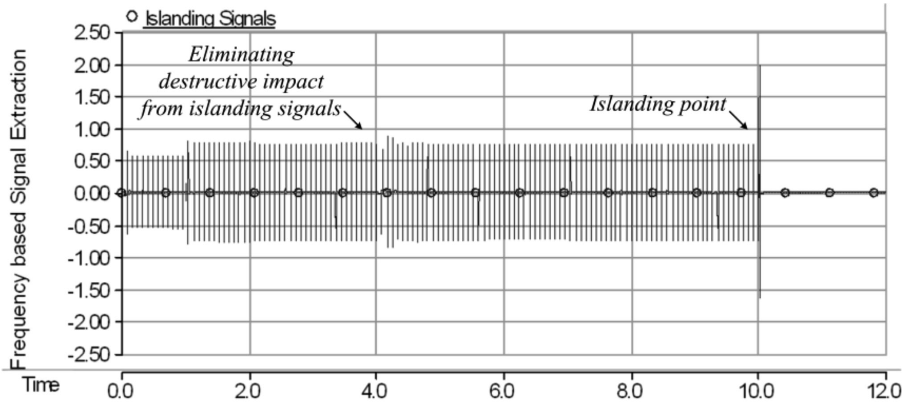


Figure 20. Islanding detection signal extraction with applying small delay in the frequency measurement.

Results show using proposed extraction methods, limits the detrimental impacts of the voltage and frequency fluctuation on IDSs extraction and makes them visible during disturbances. Using Equation (4), the strength of the signal is lesser 1%. Small *k* shows the proposed method can detect the weak IDSs at PCC. It should be noted that in previously published work, the *k* (signal strength) has to be over 4% for reliable detection. Hence, this resulted in significant reduction in the interface devices cost since smaller transformer and lower rated power electronic components can be used. Moreover, the proposed method is capable of detection islanding phenomenon in presence of multiple DG units. Furthermore, the proposed technique has improved the detection sensitivity whereby less miss-detection due to noises is observed. The study confirms the superiority of the proposed method over the existing signal extraction methods.

Nomenclature

ADM	Active detection methods
AFD	Active Frequency Drift
ALPS	Adaptive Logic Phase shift
CDM	Communication Based detection methods
DG	Distributed Generation
IDM	Islanding Detection Methods
NDZ	None-Detection Zone
PCC	Point of Common Coupling

PDM	Passive detection methods	
PJD	Phase Jump Detection	
PLL	Phase Luck Loop	
PLS	Power Line Signaling	
ROCOF	Rate of Change of Frequency	
ROCOFOP	Rate of Change of Frequency Over Power	
ROCOP	Rate of Change of Output Power	
ROCOV	Over/Under Frequency monitoring, Rate of Change of Voltage	
SD	Signal Detector	
SG	Signal Generator	
SMS	Slip Mode frequency Shift	
VDM	Voltage Detection Method	
VS	Vector Shift	
t	Time constant	
w	Angular speed	
P_{DG}	Generated active power by DG	
P_{Load}	Active power demand in the island	
Q_{DG}	Generated reactive power by DG	
Q_{Load}	Reactive power demand in the island	
□P	Active power generated by the grid	
□Q	Reactive power generated by the grid	
V_{ph}	Phase voltage	
V_{PCC}	Three-phase voltage at PCC	
$V_M(t)$	Three-phase voltage at signal generator terminal (after transformer)	
U_L	Rated phase-to-phase voltage at the signal generator	
V_{Signal}	Signal strength	
V_d, V_q	Voltage at *d*-*q* frame	
L_{Selfl}	Self-inductance of the system	
L_T	Signal transformer inductance	
P_{Is}	Generated active power in island mode	
P_{Nrm}	Generated active power in grid connected mode	
Q_{Is}	Generated reactive power in island mode	
Q_{Nrm}	Generated active power in grid connected mode	
Q_f	Quality factor	
R	Resistance	(Ω)
L	Inductance	(L)
C	Capacitance	(F)

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