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Full Length Research Paper

Investigation of a new islanding detection method for distributed power generation systems

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Distributed power generation systems (DPGSs) require reliable islanding detection algorithms (passive or active) in order to determine the electrical grid status and operate the grid connection control system properly. This paper proposes a new islanding detection method for any possible network loading based on utilizing and combining various system parameter indices. In order to secure the detection of islanding, eight intentional disturbances are imposed to the system under study in which two sets of them simulate the islanding condition. The proposed technique uses the adaptive notch filters for extracting the frequency of oscillation of generator's output waveform as one of the output parameter indices. An advantage of this technique is that it does not need to vary the islanding detection boundaries under various system loading conditions.

Key words: Islanding detection, distributed generator, adaptive notch filter.

INTRODUCTION

Deployment of distributed generators (DG) within distribution network is becoming more attractive due to many benefits that small scale generation can potentially provide to power utilities. Despite the favorable aspects of grid connected DGs can provide to the distribution system, a critical demanding concern is islanding detection and prevention. Islanding is a condition where the DG supplies power and is not under the direct control of the utility. An islanding condition creates safety hazard and may cause damage to power generation and power supply facilities as a result of unsynchronized re-closure. Consequently, the ability to quickly detect a power island is a critical safety requirement for both the DG owners and utilities. This is reflected in IEEE std. 1547-2003 and IEEE std. 929-2000 which specify that a DG should cease to energize the electric power system within specified time once an island occurs. In general, islanding detection methods are classified into two main groups: Active and passive methods (Pai and Huang, 2001; Velasco et al., 2010).

Active islanding detection methods interact with the system operation. This could be done by injecting a distorted current waveform, using a frequency pattern, or by varying the output power of the DG continuously. Island loading for which the islanding detection method fails to detect islanding is known as the non-detection zone (NDZ). Despite that active methods are characterized by small NDZ, these methods affect the power quality of the distribution system. They are most commonly applied to inverter based DGs. Active methods include active frequency drift (AFD), output power variation and slip mode frequency shift (SMFS), and etc. (Huang and Pai, 2000;Trujillo et al., 2010).

Passive islanding detection techniques depend on measuring system parameters and setting thresholds for the measurable parameters. Passive islanding detection methods can be applied to any type of dispersed generation whether the DG is of synchronous type or inverter based type. The main challenge when designing a passive islanding detection method is to choose the most significant parameter and its threshold value to detect islanding for almost all loadings while avoiding nuisance tripping. Thresholds are chosen such that the islanding detection algorithm will not operate for other disturbances on the system. As a result, passive methods

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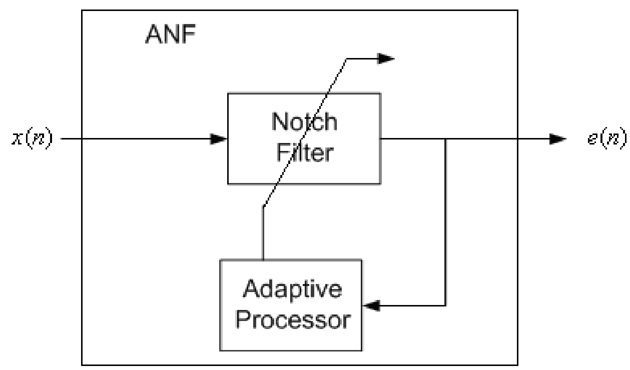

Figure 1. Adaptive notch filter model.

suffer from large NDZ (Zeineldin et al., 2007; Lee and Park, 2010).

In practice, two types of DG technologies are commonly used for applications: Inverter based and rotating machine technology. This paper proposes a new islanding detection approach for rotating DG machines of synchronous type. This approach utilizes and combines various system parameter indices in order to secure the detection of islanding for any possible network loading. The proposed approach uses the generator's terminal voltage and current measurements to derive seven parameter indices namely; voltage, power factor, rate of change of voltage, rate of change of reactive power, rate of change of active power, rate of change of frequency and the frequency of oscillation of the generator's output waveform. In this paper a new method based on adaptive notch filters is introduced in order to extract the frequency of oscillation of the generator's output frequency waveform.

In order to demonstrate a comprehensive anti-islanding algorithm, the peak of aforementioned parameter indices are extracted using signal processing after applying eight sets of intentional disturbance to the grid under study. Two sets of disturbances simulate islanding condition and the other six sets of disturbance are turbulences that taking place in a situation in which distributed generator operate parallel with the main electric power system. With the observation of the changes of the pattern of parameter indices after applying each disturbance, it is tried to present an anti-islanding protection algorithm for distinction between islanding condition and other turbulences.

Extracting signal parameters using notch filters

Estimation of signal parameters via fast Fourier transform (FFT) which is widely used to extract the frequency of signal modes causes wrong results. According to the facts that the frequency of oscillation of disturbances is not an integer multiple of the fundamental frequency of the grid, and the waveform of oscillation of disturbances is not a pure sine wave and has a damping factor, FFT algorithm fails and the phenomenon of leakage takes place. In order to overcome the aforementioned drawback, a new method based on adaptive notch filters is introduced here to extract the frequency of oscillations of the generator's output frequency waveform. Adaptive notch filters (ANF) utilize a clove filter as the main filter that does not pass a unique frequency. In Figure 1, the model of an adaptive system based on notch filters is depicted. In such a system by using adaptive algorithms, it is tried to set the parameters of the filter in order to minimize the mean square error of the output signal ($e(n)$). In this way, the frequency of the notch filter is equal to the frequency of the main component of the input signal ($x(n)$) (DeBruner and Torres, 2007).

The higher the gradient of a surface at a point, the steeper the line is at that point. A negative gradient means that the surface slopes downwards. This is the basis of the steepest descent method which is implemented to minimize the mean square error (MSE) of the output signal in Figure 1:

$$MSE = E[e(n)] \tag{1}$$

$$a(n+1) = a(n) - \mu.\nabla\left(E\left|e(n)^2\right|\right) \tag{2}$$

where, $a(n+1)$ and $a(n)$ are the parameters of the filter in the stage of $(n+1)$ and (n) respectively, and μ is the step size. According to the large amount of calculations to compute the gradient of the mean square error, the least mean square error presents an approximation for this gradient:

$$\nabla_a\left(E\left|e(n)^2\right|\right) \cong 2e(n)\nabla_a(e(n)) = 2e(n)\frac{\partial e(n)}{\partial a} \tag{3}$$

Many structures have been developed for the transfer function of the notch filter, which the most famous ones are the direct form and the lattice form. Lattice form is selected in this paper because of the better performance in adaptive algorithms. The transfer function of the lattice notch filter is given by:

$$H(z) = \frac{1+\sin\theta_2}{2} * \frac{1+2\sin\theta_1 Z + Z^2}{1+\sin\theta_1(1+\sin\theta_2)Z + \sin\theta_1 Z^2} \tag{4}$$

where, θ_1 and θ_2 are related to the frequency of the filter and bandwidth respectively:

$$w_0 = \theta_1 + \pi/2 \qquad \sin\theta_2 = \frac{1-\tan(B/2)}{1+\tan(B/2)} \tag{5}$$

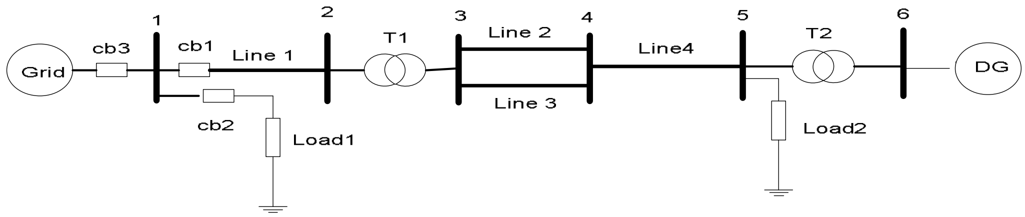

Figure 2. Single line diagram of system under the study.

In the aforementioned equation, B is the bandwidth by decreasing B, the time constant of the filter will be increased. In other word, ideal filter causes a delay on the ultimate output. With minimizing of the cost, function of $\sum_{i=1}^{n} e(i)$ in the lattice form, a unique global minimum point for each θ_1 can be obtained which is independent of θ_2. Adaptive algorithm for the lattice form is given by Equation (6) which can be utilized to set the θ_1 as a filter parameter to minimize the mean square error of the output signal.

$$\theta_1(k+1) = \theta_1(k) + \mu \frac{\partial E(k)}{\partial \theta_1} \quad (6)$$

MATHEMATICAL REPRESENTATION

The equation of motion for a synchronous machine connected to an infinite bus considering the simplified second order system, results in state equation that could be given by:

$$\frac{d}{dt}\begin{bmatrix} \Delta w_r \\ \Delta \delta \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_S}{2H} \\ w_0 & 0 \end{bmatrix} \begin{bmatrix} \Delta w_r \\ \Delta \delta \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} \\ 0 \end{bmatrix} \Delta T_m \quad (7)$$

in which the parameters are, H : Machine inertia, K_S : Synchronizing coefficient, K_D : damping coefficient, w_0 : Angular synchronous speed, w_r : Rotor speed, T_m : Mechanical torque and δ : Rotor angle.

Considering the aforementioned dynamic equation, the frequency of oscillation of a synchronous DG can be represented by:

$$f_{osc} = \left(\frac{w_0 K_s}{2H} - \frac{w_0^2 K_S^2}{16 H^2} \right)^{0.5} \quad (8)$$

For an islanded synchronous DG, there will be no synchronizing torque and K_S, consequently f_{osc} is equal to zero. Inclusion of automatic voltage regulator (AVR) in the model will result in higher synchronizing torque and the frequency of oscillation in islanding condition exceeds from whatever stated in (8), but it is smaller than the parallel condition (Kundur, 1994). Therefore, it seems that the condition of $f_{osc} < f_{\max}$ on the output frequency waveform can be utilized to be distinct between islanding and other turbulences. This concept can be examined more precise with reference to a typical grid connected distributed generation shown in Figure 2 (Salman et al., 2001). It basically consists of a DG connected to a Grid with an assumed fault level of 3436 MVA. This connection is organized through a point of common coupling (PCC) at bus1. The DG consist of ten 2.5 MVA, 11 KV synchronous generators.

Three sets of disturbances under two different operation states (OS) of the distribution system are imposed to the system under the study:

Set1: Tripping of cb1 to simulate the condition of islanding;
Set2: Loss of parallel feeder (Line2);
Set3: Sudden decrease of the Load2 by 40%
OS1: Maximum system loading (1.25 p.u.).
OS2: Minimum system loading (0.25 p.u.).

Using adaptive notch filters to extract the frequency of oscillation of disturbances under each of the operating states is shown in Figure 3. As the results show, the frequency of oscillation is extremely affected by the loading condition. In other words, by assigning a frequency threshold to detect the islanding under a certain operating state, it may result in mall operation and nuisance tripping under other operating states when a non-islanding turbulence occurs. Thus to present a comprehensive algorithm, it is required to combine the frequency of oscillation with other parameter indices.

PROPOSED ISLANDING DETECTION METHOD

The concept of the proposed method is based on utilizing and combining various system parameter indices in order to secure the detection of islanding for any possible network loading. The proposed method uses the generator's terminal voltage and current measurements to derive seven parameter indices namely; voltage

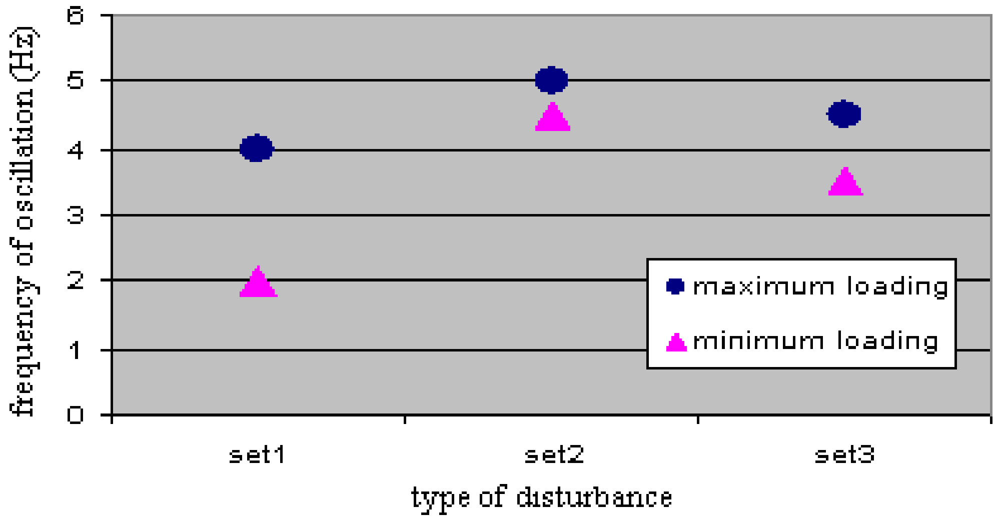

Figure 3. Frequency of oscillation of generator's output.

(V), power factor (θ), rate of change of voltage (dV/dt), rate of change of reactive power (dQ/dt), rate of change of active power (dP/dt), rate of change of frequency (df/dt) and the frequency of the oscillations of the generator's output waveform (f_{osc}) which is extracted by using adaptive notch filters.

In order to demonstrate a comprehensive islanding detection algorithm for anti-islanding protection, the peak of the aforementioned parameter indices are extracted in a 0.05 s timing window using signal processing after applying eight sets of intentional disturbances to the grid under the study of Figure 2. Two sets of the disturbances simulate the islanding condition. With the observation of the changes of the parameter indices pattern after applying each disturbance it is tried to present a anti-islanding protection algorithm for distinction between islanding condition and other turbulences while the distributed generator is operating parallel with the main system.

Eight sets of disturbances which are imposed intentionally are defined as follows:

1. Set1: Tripping of the circuit breaker cb1 to simulate the condition of islanding
2. Set2: Tripping of the circuit breaker cb2 to simulate the isolating of PCC bus load
3. Set3: Tripping of the circuit breaker cb3 to simulate the condition of islanding
4. Set4: Three phase fault on the bus 6
5. Set5: Switching a capacitor bank on the bus 6 with the capacity of 4 MVAR
6. Set6: Sudden decrease of the loading on the distribution system by 40%
7. Set7: Loss of parallel feeder (line2)
8. Set8: Operation of tap changer on the PCC bus

Each set of these disturbances is simulated under different PCC bus and distribution system operating states. The operating states are: low loading with the range of 0.25 p.u, normal loading with the range of 0.5 p.u and high loading with the range of 1.25 p.u. These loading conditions are conducted to the system under the study with the aid of load1 and load2 incorporated to the PCC and distribution system loading respectively.

1. Low distribution system loading with low PCC loading;
2. Low distribution system loading with normal PCC loading;
3. Low distribution system loading with high PCC loading;
4. Normal distribution system loading with low PCC loading;
5. Normal distribution system loading with normal PCC loading;
6. Normal distribution system loading with high PCC loading;
7. High distribution system loading with low PCC loading;
8. High distribution system loading with normal PCC loading;
8. High distribution system loading with high PCC loading.

The total number of simulated disturbances under aforementioned operating states is 72 (eight sets of disturbances time nine operating states) events. The consequences of these training events shown in Figures 4 to 10 are interpreted in terms of the seven aforementioned parameter indices. In these figures, the kind of the disturbances is categorized on the horizontal axis such that the set i represents the i'th disturbance. On the vertical axis, the peak of the parameter indices are indicated within a 0.05 s timing window after applying each set of disturbances. Since nine various operating states are defined, on the vertical axis of each set of disturbances it is marked nine various quantities for the peak of the parameter indices for occurring of each disturbance. In this manner, each of these nine various quantities represent the peak quantity of the parameter indices for one of operating states.

The main characteristic of these graphs that are depicted in Figures 4 to 10 can be categorized as follows:

1. The changes of active power have no influence on the grid frequency while distributed generator is operating parallel to the main grid. This expression is not true in the islanding condition and consequently the grid frequency and the output active power of distributed generator will change simultaneously.
2. The small frequency of oscillation of generator's output waveform discussed previously in mathematical representation section can verify the occurrence of islanding.
3. There are states that are characterized by a voltage that is in the permissible domain, a power factor that is low, a rate of change of reactive power and a rate of change of frequency that are high. In this manner, distributed generator responds to a large load

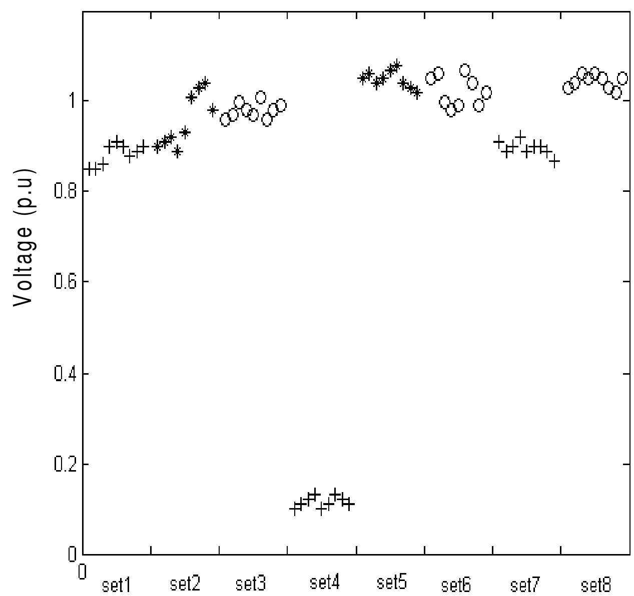

Figure 4. Voltage under all disturbances.

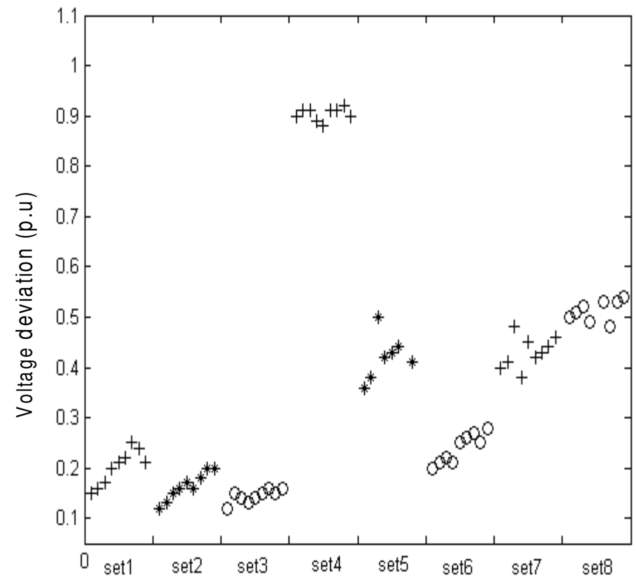

Figure 6. Voltage deviation under all disturbances.

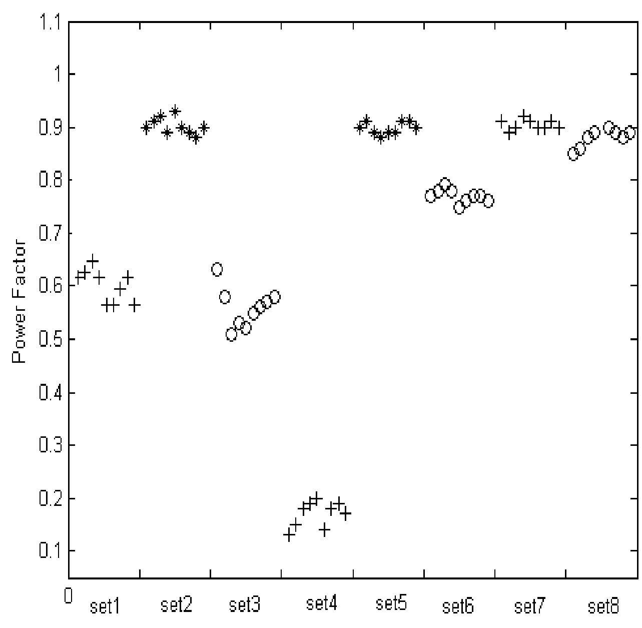

Figure 5. Power factor under all disturbances.

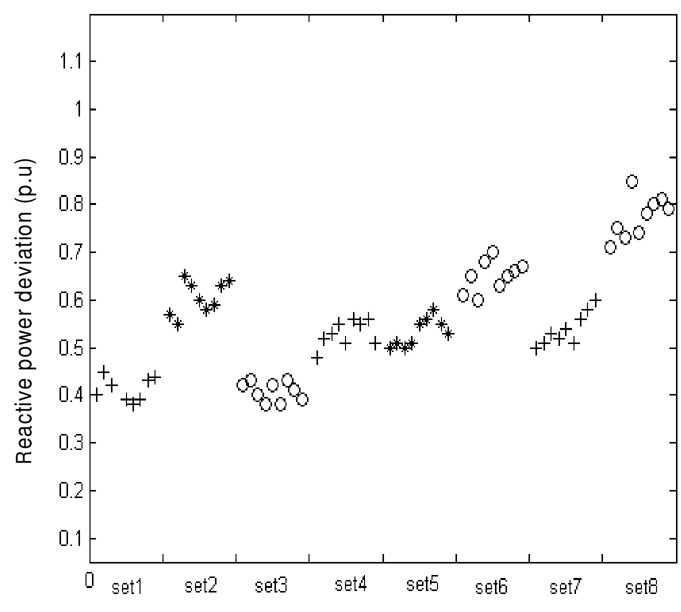

Figure 7. Reactive power deviation under all disturbances.

variation.

4. The states that are described by a rate of change of reactive power and a power factor that are low indicate the passing of the excitation system from transient state and reaching to a steady state. In this state, a high rate of change of active power and frequency indicate an islanding condition.

5. There are states that the frequency is steady which shows that, although the voltage derivative may exist, the power system is reasonably stable. This happens when the system voltage varies due to tap changer action of the substation transformer. Under these conditions, the tap changer would be responding to minor load variations.

Based on the training data shown in Figures 4 to 10 and the data analysis which are hinted previously, the anti-islanding protection algorithm is proposed in Figure 11. The proposed algorithm contains twenty pedestal nodes in which nine nodes are decision making terminals at the nodes of 9, 10, 12, 13, 15, 16, 19 and 20.

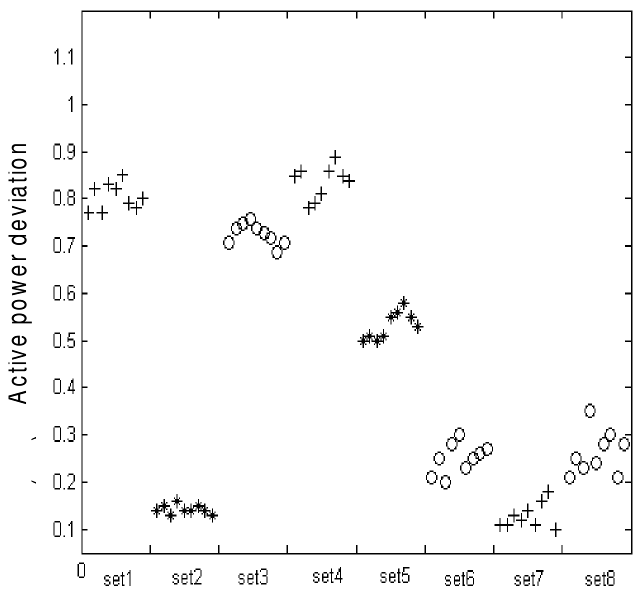

Figure 8. Active power deviation under all disturbances.

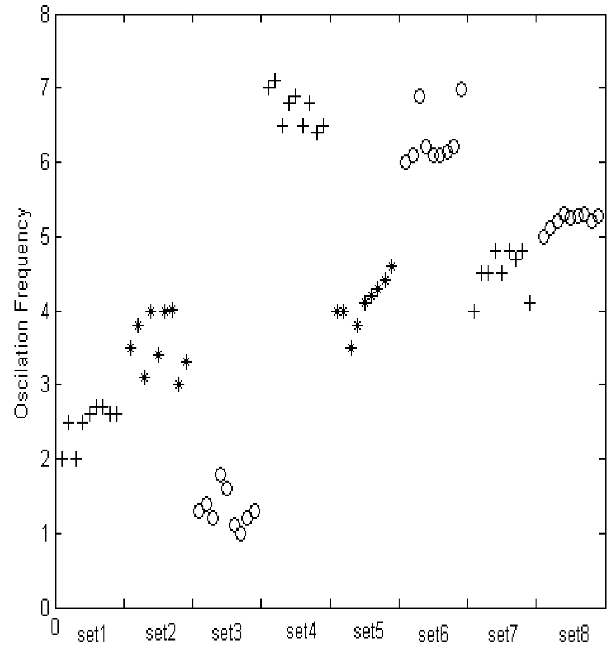

Figure 10. Oscillation frequency under all disturbances.

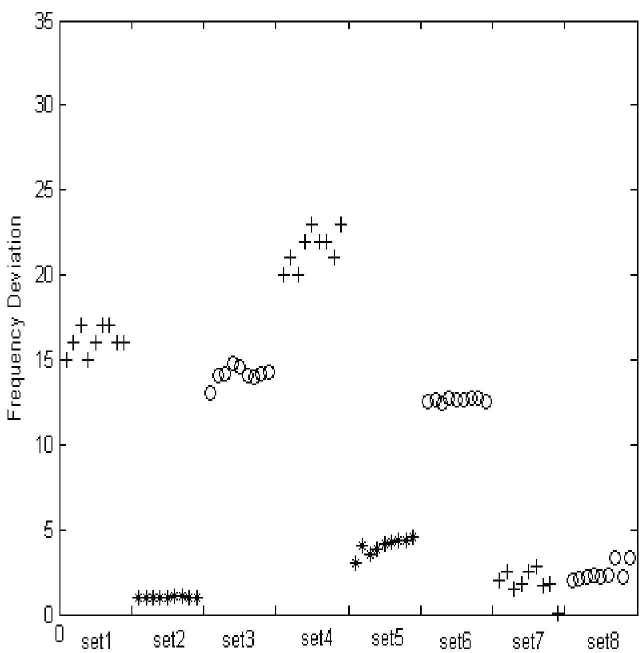

Figure 9. Frequency deviation under all disturbances.

The nodes of 4, 5, 6, 7, 8, 11, 14, 18 are conditions which are needed to determine boundaries to pass them. These boundaries are namely; $k_{1\max}$ to $k_{8\max}$. Therefore it is required to determine these boundaries carefully. Another factor which considerably affects the performance of the proposed algorithm is assigning measurement window of the peak of the parameter indices after applying each disturbance.

In order to determine the boundaries as well as the desired timing window for measuring the peak of the parameter indices, several simulations are conducted to the whole buses of the system under study and with regard to the dependency of the parameter indices to the grid topology, the boundaries of the condition nodes of the algorithm and the measurement window of the peak parameter indices are determined in such a way that the proposed algorithm has a powerful ability to distinguish between islanding and the other disturbances that occur when the DG is operating parallel to the main grid. Obtained results indicate:

1. The desired measurement window is 0.05 s that is implemented at the node2 of the algorithm
2. The suitable boundaries are $k_{1\max}$ to $k_{8\max}$ which are stated in Table 1.

By sweeping in the direction of the dictated algorithm nodes after applying each set of disturbances that are categorized into two classes of islanding (set1, set3) and non-islanding, it is indicated that the nodes 10, 12,13,16,17 and 20 are the normal operating states of the system, therefore, it is needed to pass to the next timing period ($t_0 + 0.05$) to measure the peak of the parameter indices. At the nodes of 9 and 15 the tracing of the load variation and the tap change operation are recognized respectively as transient states, therefore, it is needed to block islanding detection process and to take into consideration a requisite time in order to damp the oscillations and then the algorithm arrives the next cycle of the measurements. At the node of 19, it is recognized as the islanding condition so it is essential that the DG cease to energize the electric power system and disconnect from the distribution system.

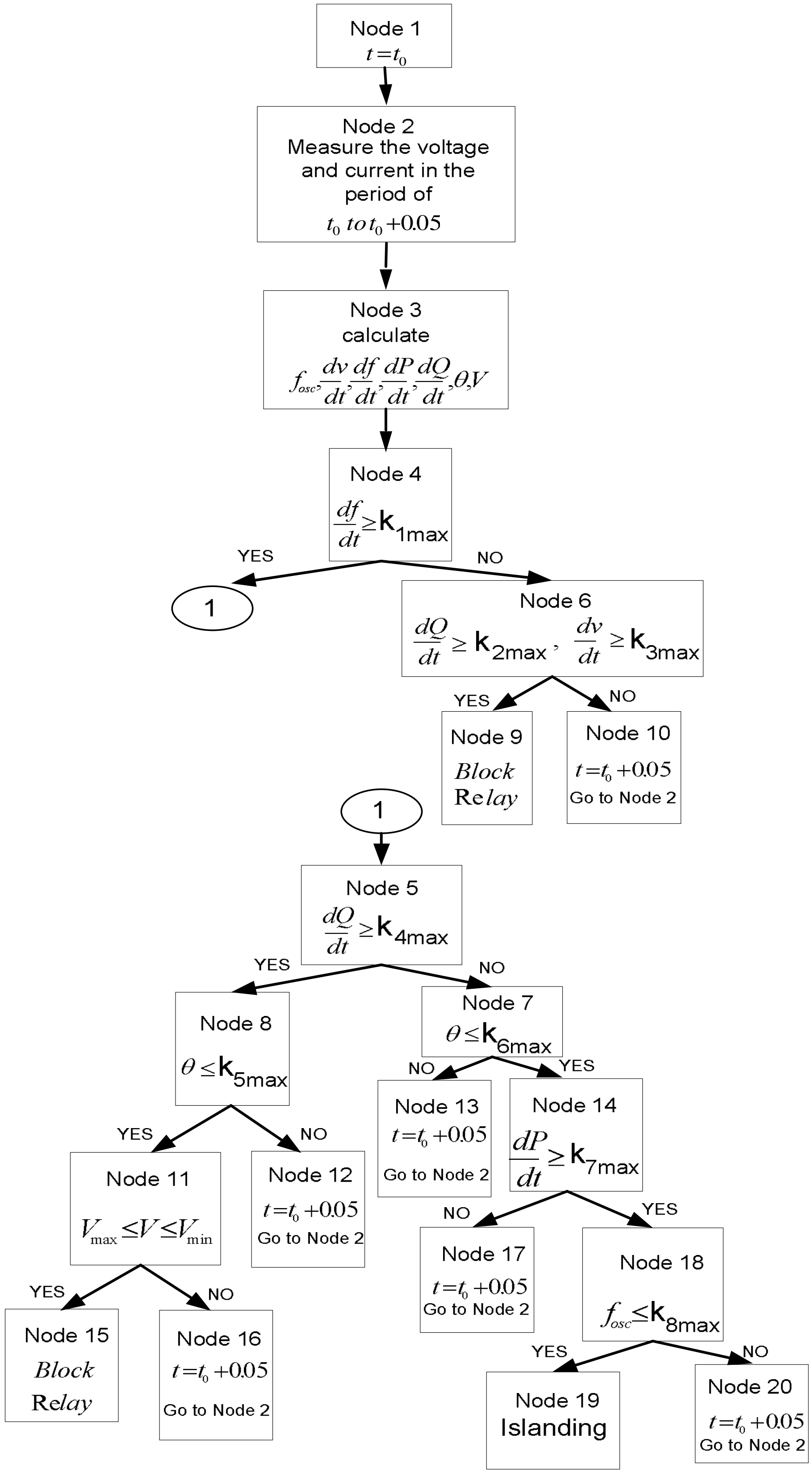

Figure 11. Proposed anti-islanding protection algorithm.

Table 1. Boundaries of the condition nodes.

$K_{i\max}$							
k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8
12	0.65	0.45	0.5	0.8	0.75	0.65	3

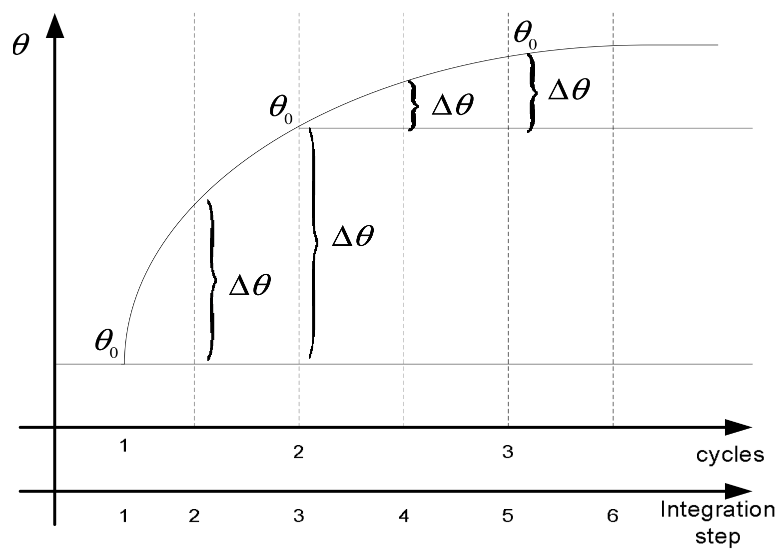

Figure 12. Algorithm implemented to represent VSR.

Comparative analysis

To illustrate the performance of the proposed algorithm, its performance is compared with the vector surge relay (VSR) which is widely used to detect the islanding condition. This comparative analysis is conducted to the system under study of Figure 2 under two different loading conditions give following.

Principle of vector surge relays

When a synchronous generator is operating in parallel with a distribution network, there is a voltage drop between the terminal voltage V_T and the generator internal voltage E_I due to the generator current passing through the generator reactance. Consequently, there is a displacement angle between the terminal voltage and the generator internal voltage. If the circuit breaker cb3 opens, the system composed by the DG and the loads becomes islanded. At this instant, the synchronous machine begins to feed a larger load because the current provided by power grid is abruptly interrupted. Consequently, the angular difference between V_T and E_I is suddenly increased. This behavior of the terminal voltage is called vector surge or vector shift. It is possible to verify that the cycle duration also changes. Vector surge relays are based on such phenomena. Vector surge relays available in the market measure the duration time of an electrical cycle and start a new measurement at each zero rising crossings of the terminal voltage. The generator terminal voltage angle θ is determined at each integration step, and a reference terminal voltage angle θ_0 is computed and updated at the beginning of each cycle. The absolute variation between these two angles $\Delta\theta = |\theta - \theta_0|$ is calculated at each integration step and compared with the angle threshold α of VSR. In an islanding situation, the cycle duration is either shorter or longer, depending on if there is excess or deficit of power in the islanded system. This variation of the cycle duration results in a proportional variation of the terminal voltage angle $\Delta\theta$, which is the input parameter of vector surge relays. If the variation of the terminal voltage angle exceeds a pre-determined threshold α, a trip signal is immediately sent to the circuit breaker. The algorithm of the VSR can be better understood through Figure 12. Usually, vector surge relays allow this threshold to be adjusted in the range from 2° to 20° (Freitas et al., 2007).

RESULTS OF COMPARATIVE ANALYSIS

Islanding scenario is conducted to the system under study of Figure 3 under two different loading conditions as follows:

1. Loading 1: Low distribution system loading with low PCC loading;

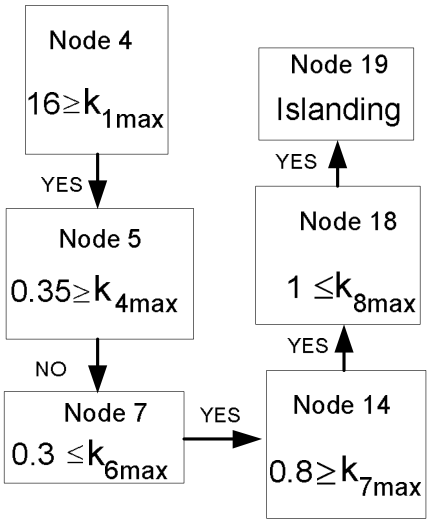

Figure 13. Operation of the proposed algorithm for loading 1.

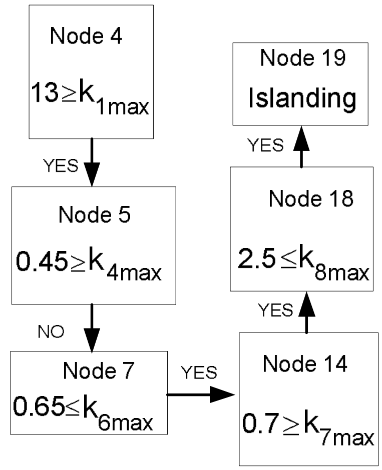

Figure 14. Operation of the proposed algorithm for loading 2.

Table 2. Operation of the VSR for loading 1.

$\theta_0 = 12^\circ$	$\Delta\theta_1$ (°)	$\Delta\theta_2$ (°)	Updating θ_0
Cycle 1	2	3	17
Cycle 2	2.5	4	23.5
.	.	.	.
.	.	.	.
.	.	.	.
Cycle 5	13	$16 > \alpha$	43

2. Loading 2: High distribution system loading with high PCC loading.

In this comparative analysis, the boundaries of the condition nodes of the algorithm are implemented by Table 1 and the threshold α for the operation of VSR is considered to be 15°. In Figure 13 and Table 2, the results of the proposed algorithm and the VSR relay for loading 1 are presented respectively. It can be seen that the proposed algorithm reaches to node 19 and successfully detects islanding condition. VSR after five cycles by $(\Delta\theta = 16) > (\alpha = 15)$ detects the islanding too. In Figure 14, for loading 2, the advantage of the proposed algorithm is depicted which is detecting of the islanding without any need to change the boundaries of Table 1. However as shown in Table 3, even after ten cycles, the VSR is disabled to detect the islanding with the threshold $\alpha = 15^\circ$ and needs to change the threshold under various loading conditions.

Table 3. Operation of the VSR for loading 2.

$\theta_0 = 12^\circ$	$\Delta\theta_1$ (deg.)	$\Delta\theta_2$ (deg.)	Updating θ_0
Cycle 1	2	3	17
Cycle 2	2.5	4	23.5
.	.	.	.
.	.	.	.
.	.	.	.
Cycle 10	8	$8.5 < \alpha$	37

Conclusion

A new technique for anti-islanding protection of distributed generation is proposed based on recognizing the pattern of the sensitivities of some parameter indices at the DG's terminal. The adaptive notch filters was capable of accurately extracting the frequency of oscillation of generator's output which is a pedestal node (Node 18) in the proposed algorithm. The technique was compared on a typical distributed generation system with the VSR and the results indicated that the proposed algorithm has a powerful ability to detect the islanding under various loading conditions.

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