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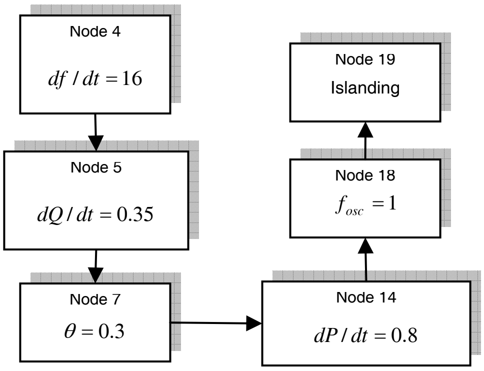

Fig. 13 Operation of the proposed algorithm for loading 1

Table 2 Operation of 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°	$16^\circ > \alpha$	43°

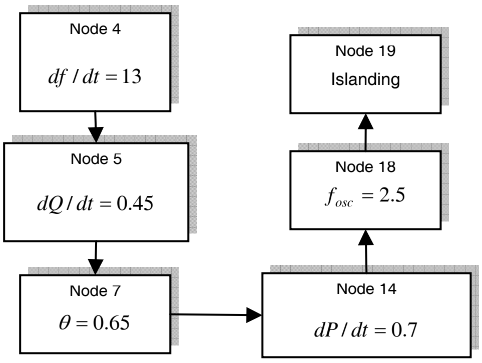

Fig. 14 Operation of the proposed algorithm for loading 2

Table 3 Operation of VSR for loading 2

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

6- Conclusion

A new technique for anti-islanding protection of distributed generation is proposed based on recognizing patterns of the sensitivities of some parameter indices at the DG's terminal. The adaptive notch filter is 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 is compared on a typical distributed generation system with the VSR technique and the results indicate that the proposed algorithm has a powerful ability to detect islanding under various system and generator loading conditions.

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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 of the DG and the loads becomes islanded. At this instant, the synchronous machine begins to feed a larger load because the current provided by the 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 phenomenon. Vector surge relays available in the market, measure the time duration of an electrical cycle and start a new measurement at each zero crossing 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 an input parameter to 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 Fig. 12. Usually, vector surge relays allow this threshold to be adjusted in the range 2° to 20° [11].

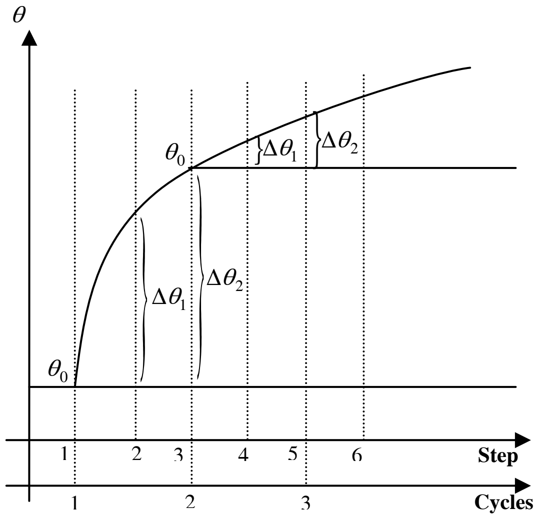

Fig. 12 Algorithm implemented to represent VSR

5-2- Results of Our Comparative Analysis

Islanding scenario is applied to the system under study of Fig. 2 under two different loading conditions as follows:

- Loading 1: Low distribution system loading with low PCC loading
- Loading 2: High distribution system loading with high PCC loading

In this comparative analysis, boundaries of the condition nodes of the algorithm are implemented according to Table 1 and the threshold α for the operation of VSR is assumed to be 15°. In Fig. 13 and Table 2, results of the proposed algorithm and the VSR relay for loading 1 are presented, respectively. It can be seen that the proposed algorithm passes the conditional nodes successfully. For example at node 4, peak parameter index $df/dt = 16$ passes the condition $df/dt > k_1$ and reaches node 19 ultimately. VSR after five cycles by $(\Delta\theta = 16) > (\alpha = 15)$ detects the islanding too. In Fig. 14, for loading 2 the advantage of the proposed algorithm is depicted which detects the islanding without any need to change the boundaries of values in Table 1. However, as shown in Table 3, even after ten cycles, with regard to $(\Delta\theta = 8.5) < (\alpha = 15)$, VSR is disabled to detect islanding. Therefore for secure islanding detection under loading 2, VSR needs to renew the threshold.

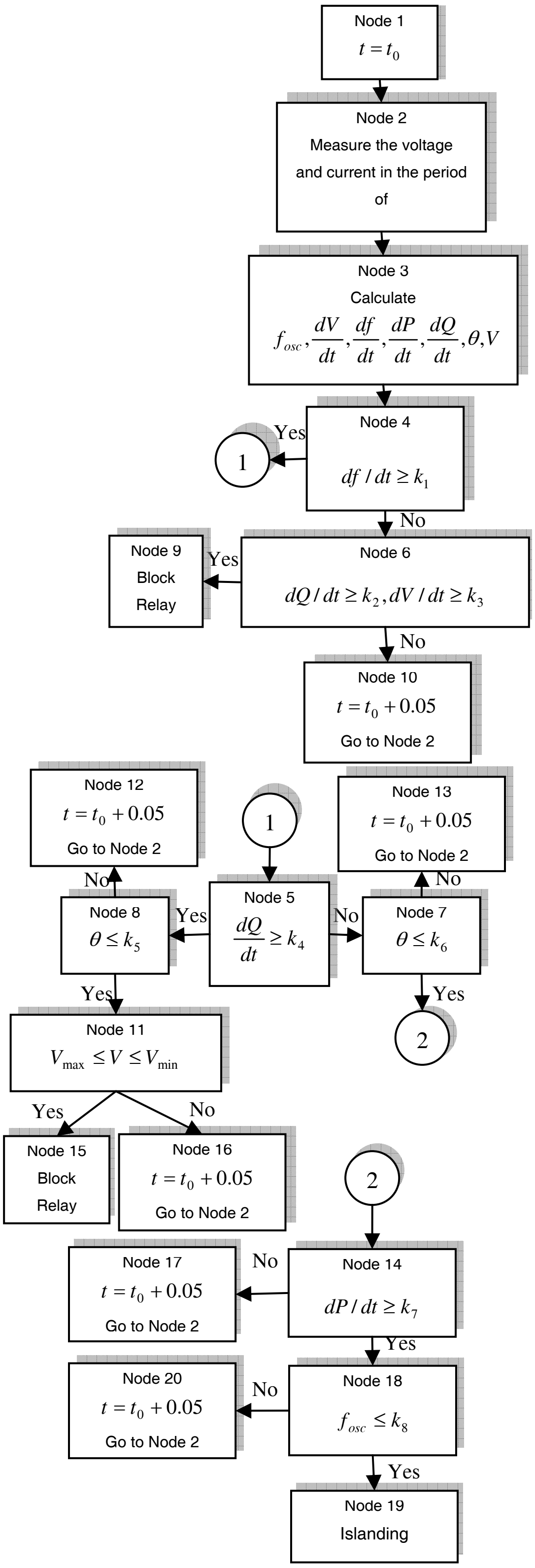

Fig.11 Proposed anti-islanding protection algorithm

Timing window, k_1 and k_4 must be selected in such a way that measured peak parameter indices, in a coincident timing window, meet these conditional nodes. For accurate detection of all eight prescribed disturbances, such consideration at all the conditional nodes and the corresponding boundaries must be regarded. So,

- The desired measurement window is 0.05 second that is implemented at the node2 of the algorithm
- The suitable boundaries are k_1 to k_8 which are stated in Table 1.

By sweeping in the direction of the dictated algorithm nodes after applying each set of disturbances 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 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 at the next cycle of measurements. Node 19 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.

5- Comparative Analysis

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

5-1- Principles of Vector Surge Relays

When a synchronous generator is operating in parallel with a distribution network, there is a needed to determine boundaries to pass them. These boundaries are; k_1 to k_8. 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 for the whole buses of the system under study. considering 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 other disturbances that occur when the DG is operating in parallel with the main grid. For example, secure islanding detection needs passing conditional nodes 4 $(df/dt \le k_1)$ and 7 $(\theta \le k_6)$ successfully.

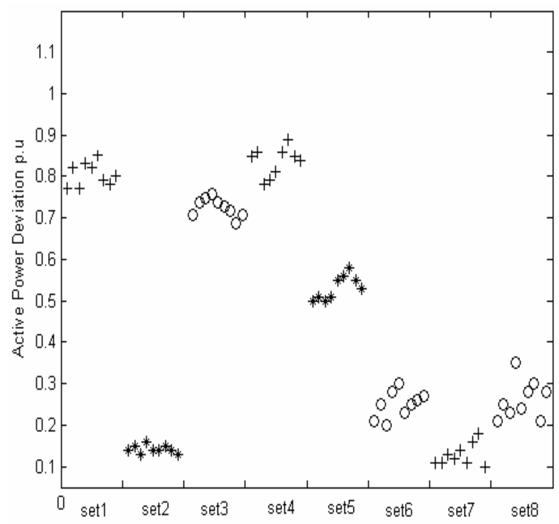

Fig. 8 Active power deviation under all disturbances

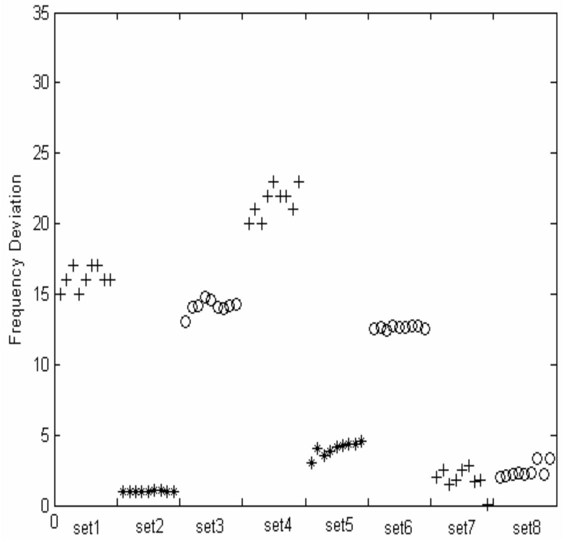

Fig. 9 Frequency deviation under all disturbances

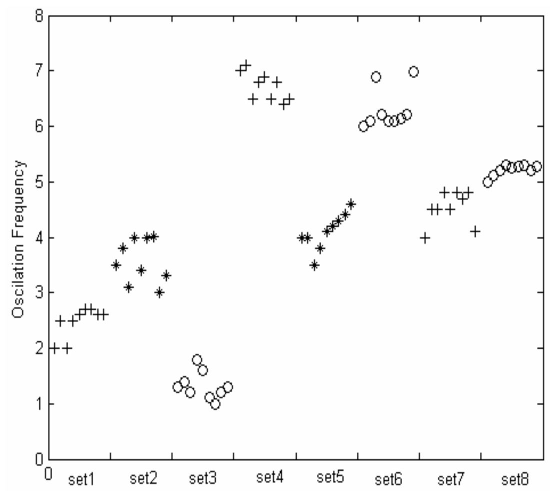

Fig. 10 Oscillation frequency under all disturbances

Table 1 Boundaries of the condition nodes

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

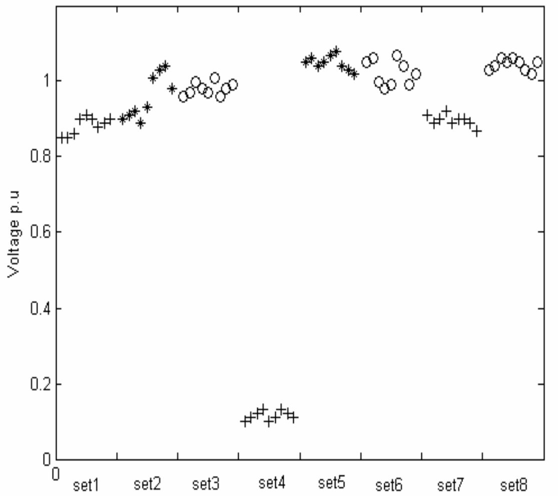

Fig. 4 Voltage under all disturbances

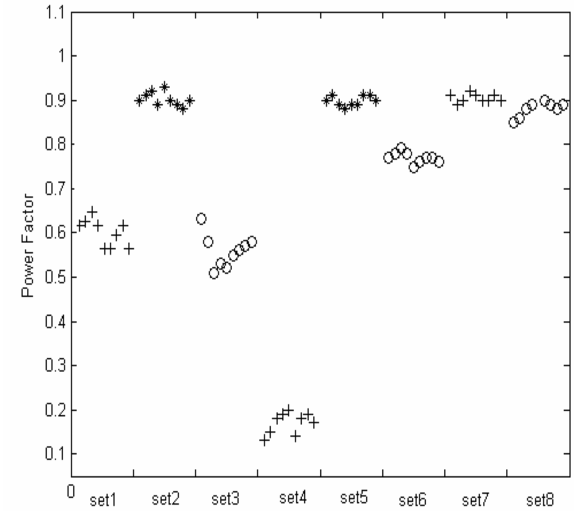

Fig. 5 Power factor under all disturbances

- 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 indicates an islanding condition.
- There are states in which 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 Figs. 4 to 10 and the data analysis which are described above, the anti-islanding protection algorithm is proposed in Fig. 11. The proposed algorithm contains twenty pedestal nodes in which nine nodes are decision making terminals at the nodes 9,10,12,13,15,16,19 and 20. The nodes 4,5,6,7,8,11,14 and 18 are those which are

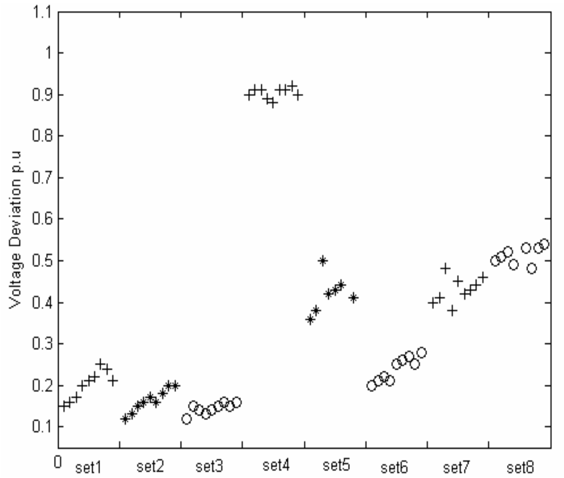

Fig. 6 Voltage deviation under all disturbances

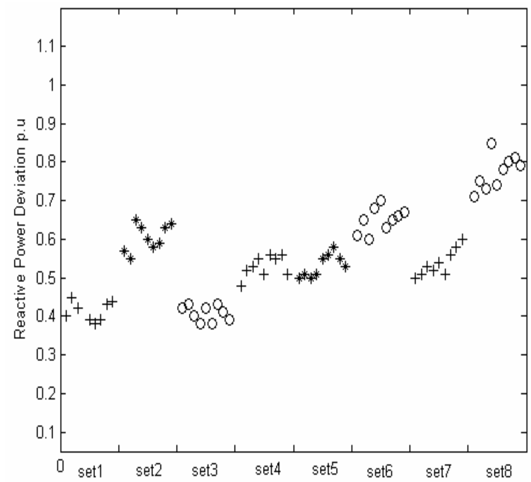

Fig. 7 Reactive power deviation under all disturbances

distributed generator is operating in parallel with the main system.

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

- Set1: Tripping of circuit breaker cb1 to simulate the conditions of islanding
- Set2: Tripping of circuit breaker cb2 to simulate the isolating of PCC bus load
- Set3: Tripping of circuit breaker cb3 to simulate the conditions of islanding
- Set4: Three phase fault on bus 6
- Set5: Switching a capacitor bank on bus 6 with capacity of 4 MVAR
- Set6: Sudden decrease of loading on the distribution system by 40%
- Set7: Loss of parallel feeder (line2)
- 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. The following loading conditions are applied to the system under study with the aid of load1 and load2 incorporated to the PCC and distribution system loading, respectively.

- Low distribution system loading, with low PCC loading
- Low distribution system loading, with normal PCC loading
- Low distribution system loading, with high PCC loading
- Normal distribution system loading, with low PCC loading
- Normal distribution system loading, with normal PCC loading
- Normal distribution system loading, with high PCC loading
- High distribution system loading with low PCC loading
- High distribution system loading, with normal PCC loading
- High distribution system loading, with high PCC loading

The total number of simulated disturbances under aforementioned operating states is 72 events (eight sets of disturbances and nine operating states). The consequences of these training shown in Figs. 4 to 10 are interpreted in terms of the seven aforementioned parameter indices. In these figures, the type of disturbance 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 second timing window after applying each set of disturbances. Since nine various operating states are defined, nine various quantities for the peak of the parameter indices are marked on the vertical axis of each set of disturbances for the occurrence of each disturbances. In this manner each of these nine various quantities represents the peak quantity of the parameter indices for one of the operating states.

The main characteristic of these graphs (Figs. 4 to 10) can be categorized as follows:

- 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 the distributed generator will change simultaneously.
- The small frequency of oscillation of generator's output waveform discussed in section 3 can verify the occurrence of islanding.
- 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 responses to a large load variation.

waveform can be utilized to distinct between islanding and other turbulences. This concept can be examined more precisely with reference to a typical grid connected distributed generation shown in Fig. 2 [10]. 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 consists 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

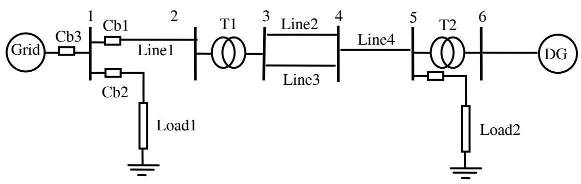

Fig. 2 Single line diagram of system under study

under 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.)

The result of using adaptive notch filters to extract the frequency of oscillation of disturbances under each of the operating states is shown in Fig. 3. As the results show, the frequency of oscillation is extremely affected by the loading conditions. In other words, by assigning a frequency threshold to detect islanding under a certain operating state, it may result in mal-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.

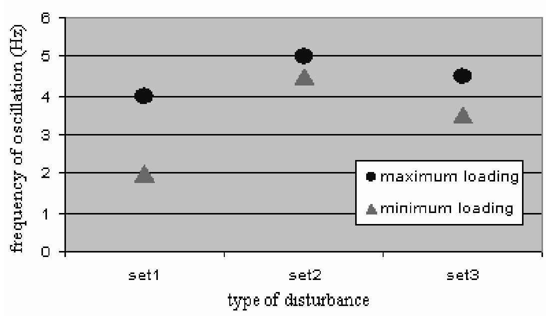

Fig. 3. Frequency of oscillation of generator's output

4- The 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 (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 frequency of oscillations of the generator's output waveform (f_{osc}) which is extracted 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 second timing window using signal processing after applying eight sets of intentional disturbances to the grid under study of Fig. 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 an anti-islanding protection algorithm for distinction between islanding condition and other turbulences while the

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 Fig. 1:

$$MSE = E[e(n)] \quad (1)$$

$$a(n+1) = a(n) - \mu.\nabla\left(E\left[e(n)^2\right]\right) \quad (2)$$

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

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

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 adopted in this paper because of the better performance in adaptive algorithms. The transfer function of the lattice notch filter is given by:

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

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

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

In (5) B is the bandwidth. By decreasing B the time constant of the filter will be increased. In other words, ideal filter causes a delay on the ultimate output. By minimizing 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:

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

3- Mathematical Representation

The equation of motion for a synchronous machine connected to an infinite bus considering the simplified second order system, results in state equations 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: synchronous angular speed, w_r: rotor speed, T_m: mechanical torque, δ: rotor angle.

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

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

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 conditions [9]. Therefore, it seems that the condition $f_{osc} < f_{\max}$ on the output frequency setting thresholds for the measurable parameters. 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 suffer from large NDZ [3].

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 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.

Some papers investigate about false operation of anti-islanding protection technique. In [4]-[7] simulation results have shown that the main factors affecting false operation are system and generator loading, amount of power exported by the generator, DG interface control, dynamic behaviour of different kind of loads, and DG reactive power.

In order to demonstrate a comprehensive anti-islanding algorithm which overcomes above mentioned drawbacks, 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 conditions and the other six sets of disturbances are turbulences that take place in a situation in which distributed generator operates in parallel with the main electric power system. With observation of the changes of the pattern of parameter indices after applying each disturbance, we try to present an anti-islanding protection algorithm for distinguishing islanding condition from other turbulences.

2- 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 leads to wrong results. According to the fact 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 above drawback a new method based on adaptive notch filters is introduced to extract the frequency of oscillations of the generator's output waveform. Adaptive notch filter (ANF) utilizes a clove filter as the main filter that does not pass a unique frequency. In Fig. 1 the model of an adaptive system based on notch filters is depicted. In such a system by using adaptive algorithms, we try 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 ($x(n)$) [8].

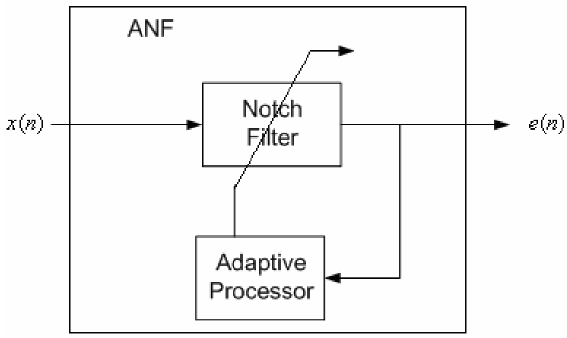

Fig. 1 Adaptive notch filter model

مجلهٔ علمی- پژوهشی

«مهندسی برق مدرس»

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Anti-Islanding Protection of Grid Connected Distributed Generators

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Abstract

A critical protection requirement for grid connected distributed generators (DG) is anti-islanding protection. In this paper, a new islanding detection method for any possible network loading is proposed 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 necessitates varying the islanding detection boundaries under various system loading conditions.

Keywords: Islanding Detection, Distributed Generator, Adaptive Notch Filter.

1- 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 favourable aspects that 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 the specified time, once an island occurs. In general, islanding detection methods are classified into two main groups: active and passive methods [1].

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 on 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), etc. [2].

Passive islanding detection techniques depend on measuring system parameters and