Intelligent Active Anti-islanding Protection for DFIG Wind Turbines Based on Artificial Immune System

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Abstract: *This paper presents an anti-islanding detection method. The proposed method employs an artificial immune system (AIS) to enhance the performance of the sandia frequency shift (SFS) method. AIS is used to optimize the SFS parameters and hence improve the islanding detection speed, reduce the non-detection zone (NDZ) and at the same time reduce the total harmonic distortion (THD). The proposed method is derived analytically and implemented using Matlab/Simulink program. A case study includes a DFIG wind turbines connected to grid are used to verify it. The optimized parameter helps to detect the islanding with least potential adverse impact on power quality.*

KEYWORDS*: Anti-islanding Detection, Sandia Frequency Shift (SFS), Non Detection Zone (NDZ), Total Harmonic Distortion (THD), Artificial Immune System (AIS), Clonal Selection Algorithm.*

1. Introduction

Distributed Generation (DG) units have become more competitive against the conventional centralized system by successfully integrating new generation technologies and power electronics. Hence, it attracts many customers from industrial, commercial, and residential sectors. DGs generally include photovoltaic, fuel cells, micro turbines, small wind turbines, and other generators [1]. Among different renewable energy sources, wind energy is expanding rapidly due to low operation cost and high efficiency [2]. DG has the ability to increase the power system efficiency, reliability and quality [3]. However, utility integrated with DG has a major concern. Undesired impacts may result from the unexpected high fault currents and possible islanding occurrences [1].

Islanding occur when a portion of utility system containing both load and distributed generation still energized while it is electrically isolated from the rest of the utility system [4]. Islanding is an undesirable phenomenon because it results in safety hazards for personnel, power quality problems for customers load. It may also cause damage to power generation, change in fault level, uncoordinated protection, voltage and frequency control problems and power supply facilities as a result of unsynchronized recloser [1, 5]. So, islanding conditions should be detected within less than 2 s [6].

Islanding detection techniques can be broadly divided into remote and local islanding detection techniques. Remote islanding detection techniques are based on the information transferred through the communication channels between the utility and the DG. The data is carried out through different communication methods. During normal operation, the circuit breaker is connected and the receivers at the DG side continuously receive signals. However, when the distribution network is islanded, the receiver will not receive the signal and islanded will be detected. This type include: impedance insertion, power line carrier communications (PLCC), signal produced by disconnect (SPD), and supervisory control and data acquisition (SCADA) [1, 7]. Remote islanding detection techniques have better reliability than local techniques; however, these techniques are complex, costly and any communication failure may lead to malfunctions throughout the system. Due to these reasons, local techniques are widely used for islanding detection for small DG systems [8].

Local islanding detection techniques are further divided into passive, active and hybrid islanding detection methods. Passive islanding detection techniques use system parameters measurement (voltage, frequency) at the DG terminals or point of common coupling (PCC). These measurements are compared with a predetermined threshold value for the purpose of detecting islanding. Passive techniques are very cost effective, as they do not require large modifications in the protection system. Few common passive technique include: Over/Under Voltage Protection (OVP/UVP), Over/under Frequency Protection (OFP/UFP), Rate of change of frequency (ROCOF), Comparison of rate of change of frequency (COROF), Rate of change of active power, Rate of change of frequency over power, Rate of change of phase angle difference (ROCOPAD), Voltage unbalance, Voltage Phase Jump Detection, and Detection of Voltage and current Harmonics methods [9 -11]. The passive techniques have the advantage of not affecting the power quality of the distribution network. However, passive techniques suffer from large non-detection zone (NDZ). Furthermore, these techniques need special care while setting the thresholds values. The passive techniques drawbacks can be overcome by active islanding detection techniques [8].

Active islanding detection techniques are based on the usage of high frequency signals or some other means to slightly perturb the system variables, such as voltage and frequency to detect the islanding. The main concept behind active techniques is when the distribution system is connected to the grid; the addition of perturbation will cause a small variation in system parameter. However, in the islanded mode, the system will observe a significant variation in system parameter, which will lead to detect the islanding. The active methods include: impedance measurement method [12], slip mode frequency shift (SMS) [13], active frequency drift (AFD) [13, 14], Sandia frequency shift [15 - 19], Sandia voltage shift [20], negative sequence current injection [21], negative sequence voltage injection [22], high frequency signal injection [23], virtual capacitor [24], phase – PLL perturbation [25], method based on voltage phase angle of inverter based DG [26], Reactive Power Variation (RPV) method [27], Mains monitoring units with allocated all-pole switching devices connected in series (MSD) [28], and method based on magnitude changing of the injected current and monitoring its voltage at the PCC [20]. Most of the active techniques are employed for inverter-based distributed generations. Active islanding detection techniques have the advantage that their non-detection zone is very small, and can detect islanding even in perfect match of generation and load demand. However, their main problem is that these techniques introduce perturbation in the system at the regular intervals of time that are unnecessary during most of the operating conditions, which often degrade the quality of power [29].

Hybrid islanding detection techniques employs the combined features of active and passive techniques. These techniques have the advantage of acquiring a very small NDZ. Furthermore, the injecting signals are not applied to the system at every instant of time. Hence, the power degradation is highly reduced. However, this combination increases the detection time for islanding phenomena [30-32].

The active methods perturb the current waveform with harmonics to detect the islanding. These methods reduce NDZ significantly; so they can detect the islanding more reliable than the passive methods. However, they affect system power quality due to the injected harmonic current. So it can be controlled using one of the computational intelligent techniques such as artificial immune system. AIS is computational paradigms that based on the natural immune system and it belong to the computational intelligence family. It is highly distributed, highly adaptive, self-organizing in nature, maintains a memory of past encounters, and has the ability to continually learn about new encounters.

Sandia frequency shift (SFS) is considered the most effective method in islanding detection that it based on frequency drifting methods. The SFS method can be used to improve the NDZ and THD by using feedback gain. But this method affect the power quality of the system and this method can be improved to reduce NDZ and THD. This paper presents a proposed technique to modify SFS anti-islanding detection method using Artificial Immune Systems (AIS). The method optimizes the parameters of the SFS method to minimize the NDZ, THD of the current waveforms and islanding detection time.

2. Sandia Frequency Shift Anti-Islanding Detection Method

SFS method is one of an active anti-islanding detection technique. SFS technique depends on using the frequency for islanding detection. It based on perturbing the power system by a distorted current and then monitors whether the system frequency exceeds its limits or not. In this method, the injected current at the point of common coupling (PCC) by the DG inverter is slightly distorted such that there is a continuous trend to change the frequency by making a zero segment in the current waveform. The ratio of the zero time to the half period time in the current waveform is called chopping fraction. When the grid is connected it is impossible to change the frequency because of the rigidity of the utility grid. However, when the grid is disconnected the frequency is forced to violate its nominal limits and then the OFP/UPF send a trip signal to shut-down the DG inverter. This method also uses a feedback gain to increase the deviation of the frequency away from its nominal value and hence accelerate the detection of islanding condition. Then the chopping fraction can be defined in the following equation

$$C_f = C_{fo} + K(f_a - f_{line}) \qquad (1)$$

Where C_{fo} the chopping fraction at no frequency error, K is an accelerating gain that does not change direction, f_a is the measured frequency of voltage at PCC (V_{pcc}), and f_{line}, is the line frequency.

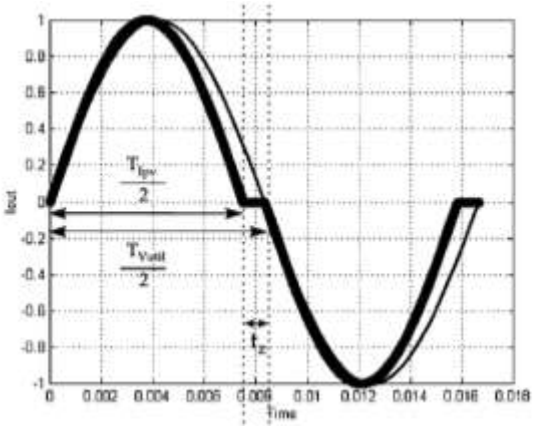

Fig. 1 . SFS current

SFS is one of the most effective methods for islanding detection. It has one of the smallest NDZs and simple in implementation. However, increasing the chopping fraction affects the system output power quality. The two parameters of the SFS method, K and C_{fo} have different effect on the NDZ of SFS schemes. The chopping factor C_{fo} changes the location of NDZ on load space, but it doesn't change the size of NDZ. Increasing C_{fo} causes adverse impact on power quality, as it perturbs the network with a distorted current. The total harmonic distortion (THD) of the output current is directly proportional to C_{fo}[33]. According to the impact on power quality; smaller values are preferred in C_{fo} setting. The feedback gain K has a positive impact on NDZ; increasing K will decrease NDZ, but it may produce negative impact on power quality of the distribution system.

It is cleared that selecting the parameters of islanding detection system is not a straightforward task. This paper presents a method for optimizing the selection of these parameters so that the best possible fast islanding detection is achieved at the lowest cost of adverse effects on power quality. The proposed method formulates SFS parameter selection as an optimization problem with main objective of minimizing NDZ while satisfying THD limit as a constraint. The following section gives detailed representation of the optimization problem.

3. Proposed Method Parameter Selection Optimization

As it is mentioned in the previous section that the selecting of the SFS parameters is a difficult problem and it can be formulated in an optimization problem as follow

3.1. Objective Function

The objective function is to minimize NDZ of the SFS, which can be expressed mathematically as:

$$\text{Min } (\Delta F_o) = f_{omax} - f_{omin} \qquad (2)$$

Where f_{omax} is the maximum value of load resonant frequency that will result in islanding operation, f_{omin} is the minimum value of load resonant frequency that will result in islanding operation. The f_{omax} and f_{omin} can be calculated as the following equations;

$$f_{omax} = f_0 + \Delta f_+ \qquad (3)$$

$f_{omin} = f_0 - \Delta f_-$ (4)

The load angle $\theta_{load}(f)$ and inverter angle $\theta_{inv}(f)$ are the same at the steady state frequency so that;

$$\theta_{load}(f) = \theta_{inv}(f) \quad (5)$$

For *RLC* load the phase angle of the load can be calculated as follow;

$$\emptyset_{load} = \tan^{-1}\left[R\left(\frac{1}{\omega L} - \omega C\right)\right] \quad (6)$$

From the definition of the quality factor Q_f and the load resonant angular frequency ω_0, one can get

$$\frac{R}{L} = Q_f * \omega_0 \quad (7)$$

$$RC = \frac{Q_f}{\omega_0} \quad (8)$$

Substituting equations (7) and (8) into (6) yields

$$\emptyset_{load} = \tan^{-1}\left[Q_f\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)\right] = \tan^{-1}\left[Q_f\left(\frac{f_0}{f} - \frac{f}{f_0}\right)\right] \quad (9)$$

The load current voltage phase angle (θ_{load}), that represents the angle by which the current leads the voltage, is given by

$$\theta_{load} = -\emptyset_{load} = \tan^{-1}\left[Q_f\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right] \quad (10)$$

$\theta_{inv}(f)$ can be calculated as in the following equation;

$$\theta_{inv}(f) = \frac{\pi}{2}(C_{fo} + K(f_a - f_{line})) \quad (11)$$

By substituting equations (10) and (11) into (5) and solving this equation yields

$$\Delta f_+ = \frac{f_0}{2Q_f}\left[\frac{\pi}{2}C_{f\,max} - 2Q_f + \sqrt{(\frac{\pi}{2}C_{f\,max})^2 + (2Q_f)^2}\right] \quad (12)$$

$$\Delta f_- = \frac{f_0}{2Q_f}\left[2Q_f - \frac{\pi}{2}C_{f\,min} + \sqrt{(\frac{\pi}{2}C_{f\,min})^2 + (2Q_f)^2}\right] \quad (13)$$

$$C_{f\,max} = \frac{\pi}{2}\left(C_{fo} + K(f_{Nmax} - f_o)\right) \quad (14)$$

$$C_{f\,min} = \frac{\pi}{2}\left(C_{fo} + K(f_{Nmin} - f_o)\right) \quad (15)$$

Where f_{Nmax} and f_{Nmin} are the maximum and minimum frequency limit according to IEEE Std. 929-2000.

3.2. Problem Constraints

Total harmonic distortion limits and accelerating gain limit are the main constraints for which the objective function in (2) is subjected:

i. Total harmonic distortion limits

Due to its negative impact on the power quality of the distribution system; THD must be limited to a preset value. According to IEEE Std.519-1992 limits THD must be less than 5% [34].

$$\frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \leq 0.05 \quad (16)$$

ii. Accelerating gain limit

The performance of the SFS is affected by the positive gain coefficient K. Better performance is achieved with larger values of K. Meanwhile increasing K will increase the current distortion and results in bad effect on system power quality.

The problem is solved using AIS to obtain the optimal values of both C_{fo} and K that minimize the NDZ and THD to acceptable values in a short time.

4. SFS Parameter Optimization Based on AIS

The immune system of vertebrates including human is composed of cells, molecules and organs in the body which protect the body against infectious diseases caused by foreign pathogens such as viruses, bacteria. To perform these functions, the immune system has to be able to distinguish between the body's own cells as the self cells and foreign pathogens as the non-self-cells or antigens. After distinguishing between self and non-self-cells, the immune system has to perform an immune response in order to eliminate non-self-cell or antigen. Antigens are further categorized in order to activate the suitable defense mechanism and at the same time, the immune system also developed a memory to enable more efficient responses in case of further infection by the similar antigen.

Clonal selection theory explains how the immune system fights against an antigen. It establishes the idea that only those cells which recognize the antigen, are selected to proliferate. The selected cells are subjected to an affinity maturation process which improves their affinity to the selected antigens.

Today, the AIS techniques are used to solve complex problems in many areas that include engineering, science, computing, and other research areas. The fundamental of AIS is inspired by the theoretical immune system and the observed immune functions, principles, and models [35, 36]. AIS mimics these biological principles of clone generation, proliferation and maturation. After the initialization of the antibodies, only antibodies recognizing the antigen with high affinity are activated to proliferate and mutate, accordingly, their affinities will increase. These antibodies can become memory antibodies after immune suppression. The following steps summarize the procedure of applying SFS–based AIS method to solve the islanding detection problem using SFS technique.

1) ***Antibody representation:*** the solution of the problem is considered as a population of antibodies. Both C_{fo} and K are considered as antibody and each parameter is represented by a gene of antibody.
2) ***Initialization:*** generate initial population between a pre-defined minimum and maximum value using a random function. If the generated solutions do not fall into the feasible range, they are ignored and the generation process repeats until the required number of initial solutions is generated. The size of the initial population is determined by making a trade-off between efficiency and quality of the solution, on one hand and reasonable computational time, on the other hand.
3) ***Affinity calculation:*** Calculate affinity between and antibodies and memory antibodies of the same K and C_{fo} according to Euclidean distance [36]:

$$affinity(x.y) = \sqrt{\sum_{i=1}^{m} (x_i - y_i)^2 / m} \quad (17)$$

4) ***Clonal operator:*** select the antibodies which have highest affinity to clone, and generate a clone set **C**. The number of clone is proportional to their antigenic affinity, the higher the affinity, the larger the clonal scale for each of the selected antibodies.
5) ***Hyper mutation:*** Each antibody in will undergo an affinity maturation process, generating a mutated set T. The mutation rate is inversely proportional to the antigenic affinity of its parent antibody, the higher the affinity is, and the smaller mutation rate will be.
6) ***Affinity modification:*** Determine the affinity among and all the elements from T, reselect the antibodies with the highest affinity as the set of partial antibodies. At the same time, eliminate all of the memory antibodies from whose affinities are smaller than the natural death threshold.
7) ***Clonal suppression:*** Eliminate those memory clones whose affinity exceeds the suppression threshold and generate the set of partial memory antibodies S.
8) ***Antigen presentation:*** Select the next antigen and return to (2). This procedure continues until all antigens have been presented to the network.
9) ***Network suppression:*** From S, eliminate those memory antibodies whose affinity violates the discrepancy of the average affinity is inferior to a prescribed threshold in four consecutive iterations. If the stopping criterion has not been met, then turn to (7).

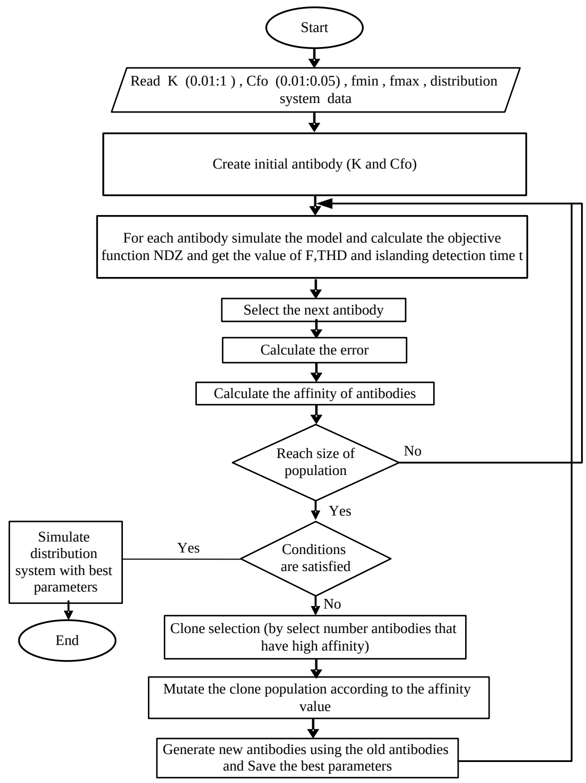

Fig. 2 . Flowchart of the modified SFS –based AIS method

5. Modelling and simulation of Test System

A 9 Mw wind farm consisting of six 1.5 Mw wind turbines connected to a grid is modeled and simulated to test the proposed method. Figure 3 and 4 show the single line diagram and the simulated system in Matlab/Simulink respectively. The wind generator using a doubly-fed induction generator (DFIG) consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting the maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.

This DG doesn't generate reactive power to the system. When the DG is isolated from the grid, it operates at the resonant frequency of the system load. The reactive power needed for the load can be obtained from any capacitor in the system. So that $Q_L = Q_C$ and this is a resonance condition. The system local load is represented by a *RLC* branch with variable resonant frequency and quality factor. The utility breaker connects the grid to the PCC in case of normal operation. For islanding condition the breaker is opened at a prescribed time. The test system is modeled and simulated using MATLAB/Simulink. The simulation parameters are presented in Table (1). The simulation is implemented in the following steps:

- The frequency is measured. If the frequency exceeds the IEEE. Std. 929-2000 limits; the OFP/UFP will generate a fault signal to shutdown the inverter.
- In case that load and DG output are closely matched, then the frequency of the network is perturbed to create a power mismatch between load and DG.
- Variation in frequency can be detected by OFP/UFP system and consequently the DG is disconnected or shutdown.
- Since this perturbation signal may induce current and voltage waveform distortion. THD of the load current is determined to check whether the IEEE limits are violated.

Table 1: Simulation parameters

Grid voltage (rms)	400 V
Grid frequency	50 Hz
LC filter	L = 18 mH
	C = 30 μF
RLC load	R = 120Ω
	L = 153mH
	C = 67μF

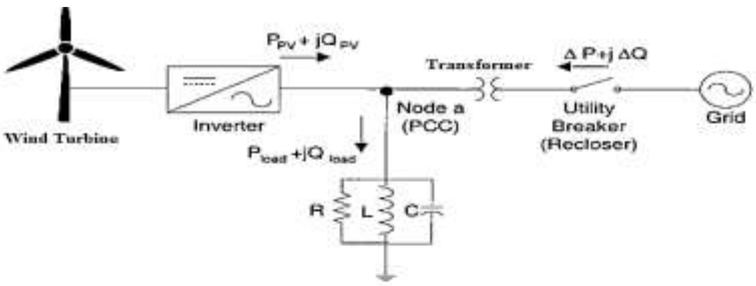

Fig. 3 . Sigle line diagram of the test system

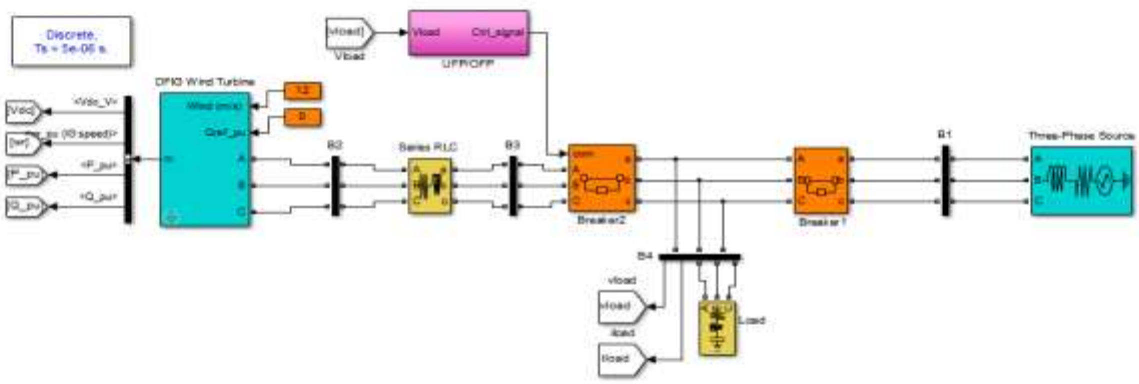

Fig. 4. Simulation of the test system using MATLAB/Simulink

6. Results and Discussion

Both the conventional SFS and the proposed modified SFS –based AIS methods are applied to the test system. A comparison between the results obtained after applying the two methods is presented below.

The conventional SFS method is applied to the test system shown in Figure 3. The simulation results show that: the feedback gain K equals to 0.108 and C_{fo} equals to 0.027 with a NDZ of 0.97025 Hz and THD of 4.048%. The utility grid is disconnected at 0.228 s. After the disconnection of the grid, the system detects the islanding condition by applying SFS method and sends a trip signal to disconnect the DG at 0.2324 s that is after 4.4 ms from the grid disconnection as shown in Figure 5(a). When the system responds to detect island, the voltage at PCC and load current begin to decay until reach steady state values and disconnect the DG as shown in Figure 5(b-c). Figure 5(d) shows the frequency change after the grid is disconnected.

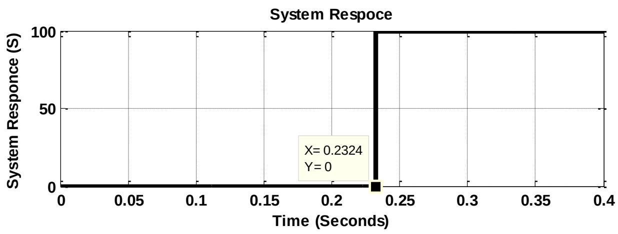

Fig. 5(a) system response

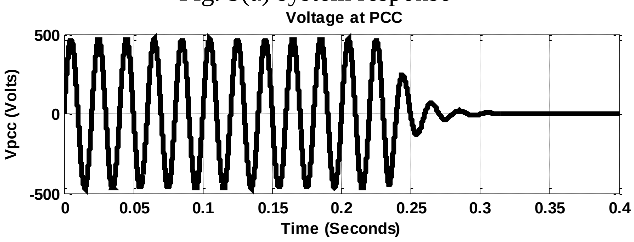

Fig. 5(b) Voltage at PCC

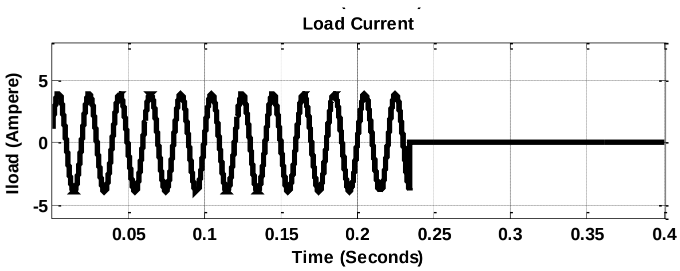

Fig. 5(c) Load current

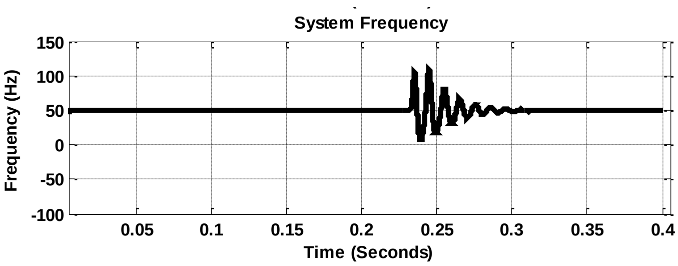

Fig. 5(d) System frequency

Fig. 5 . SFS anti-islanding detection method output waveform

The modified SFS anti-islanding method that based on based AIS is applied to the test system. Figure 6 shows population and cloning of the best affinity values. According to this method the optimal values of the feedback gain K and C_{fo} are 0.13 and 0.026 respectively, with a NDZ of 0.9641 Hz and THD of 3.35%. From the Figure 7(a) the system response for detecting the island condition at 0.22924 s so that the DG is disconnected after 1.24 ms from the grid disconnection as the grid is disconnected at 0.228 s. When the grid is disconnected, the voltage at PCC and the load current become to decay after sending a trip signal to disconnect the DG, this shown in Figure 7(b-c). Whereas Figure 7(d) shows the frequency change after the grid is disconnected.

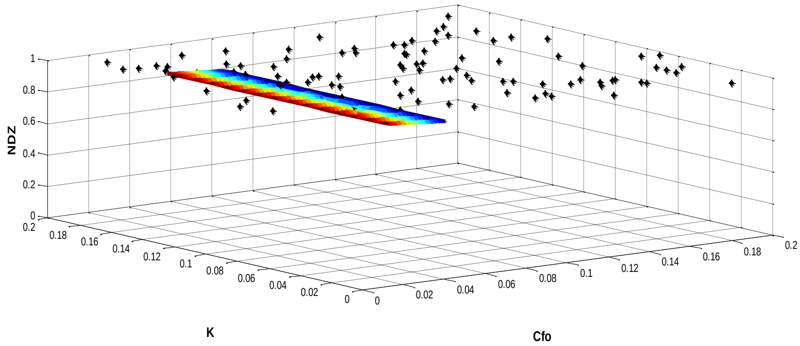

Fig. 6. Population and cloning of the best affinity values

The results show that conventional SFS has THD of 4.048% and the DG is disconnected after 4.4 ms from the grid disconnection. For the modified SFS method the THD is 3.35% and the DG is disconnected after 1.24 ms from the grid disconnection. As shown in Figure 8(a), the system response for sending the trip signal to the DG to detect islanding condition is more effective by applying the modified SFS than the conventional SFS method. The proposed method decreases the time of islanding detection to just 28.18% of that attained by the conventional method. At the same time the proposed method decreases the THD to 82.75% of the THD obtained by the conventional method and reduces the NDZ. The results prove the efficiency and speed of the proposed method in islanding detection. The comparison between the two methods is shown in Figure 7.

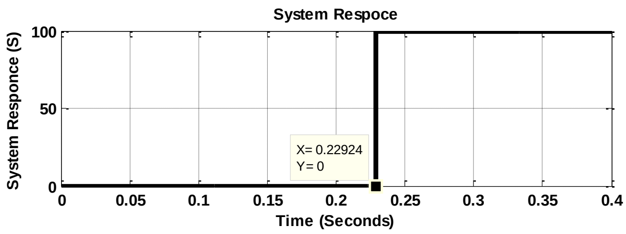

Fig. 7(a) System response

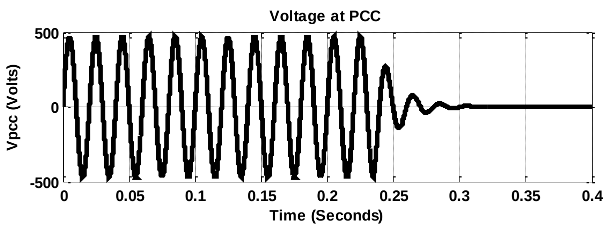

Fig. 7(b) Voltage at PCC

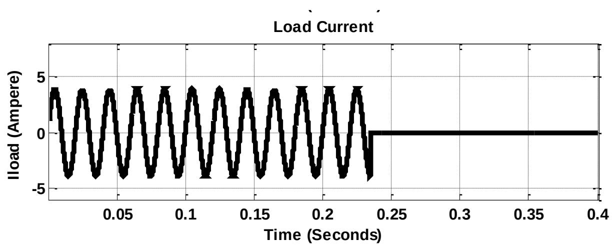

Fig. 7(c) Load current

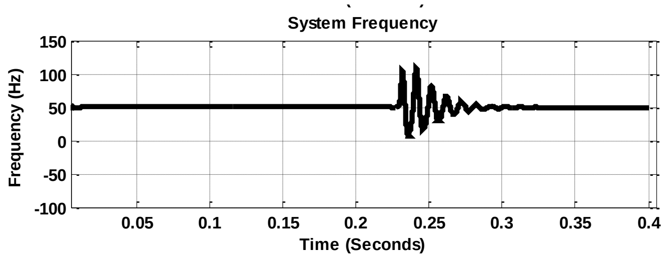

Fig. 7(d) System frequency

Fig. 7 . Modified SFS anti-islanding detection method based on AIS output waveform

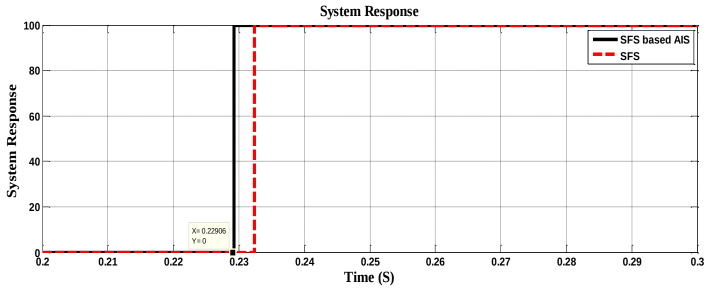

Fig. 8(a) . System response

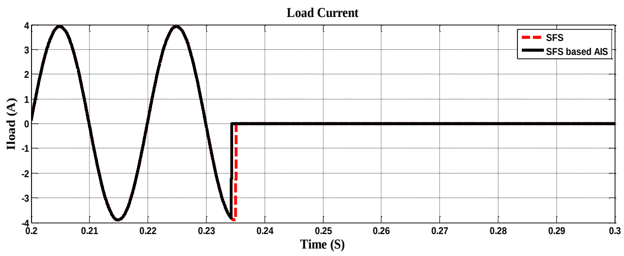

Fig. 8(b) . Load current

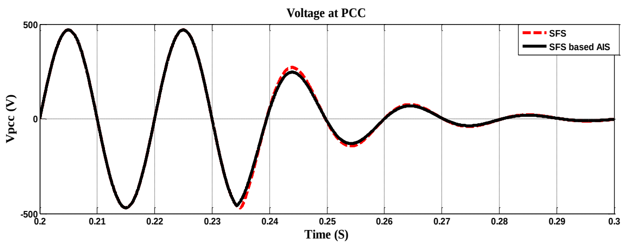

Fig. 8(c) Voltage at PCC

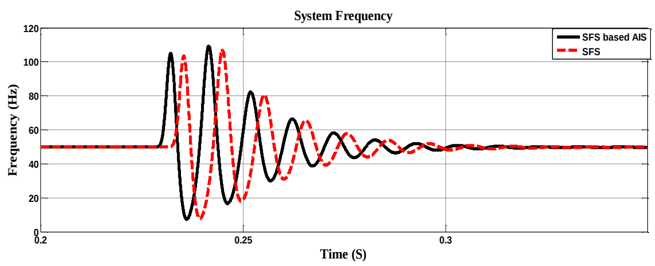

Fig. 8(d) System frequency

Fig. 8. Comparison between the modified SFS and the conventional method

7. Conclusion

A method for islanding detection is introduced based on the SFS. SFS is an active anti-islanding detection method. The proposed method uses an artificial intelligence technique based AIS with the conventional SFS method to improve the SFS method performance regarding THD reduction, island detection speed and non-detection zone reduction. The proposed method has been applied to a test system and its performance was compared to the conventional SFS method; the proposed method performed better in reducing the THD of the voltage at the PCC, narrower non-detection zone and faster in detecting islanding when it takes place.

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