A Novel Anti-Islanding Method for Utility Interconnection of Distributed Power Generation Systems

In-Ho Hwang†

Abstract - A novel anti-islanding method for the distributed power generation system (DPGS) is proposed in this paper. Three different islanding scenarios are explored and presented based on the analysis of real and reactive power mismatch. It is shown via investigation that islanding voltage is a function of real power alone, where its frequency is a function of both real and reactive power. Following this analysis, a robust anti-islanding algorithm is developed. The proposed algorithm continuously perturbs (±5%) the reactive power supplied by the DPGS while simultaneously monitoring the utility voltage and frequency. In the event of islanding, a measurable frequency deviation takes place, upon which the real power of the DPGS is further reduced to 80%. A drop in voltage positively confirms islanding and the DPGS is then safely disconnected. This method of control is shown to be robust: it is able to detect islanding under resonant loads and is also fast acting (operable in one cycle). Possible islanding conditions are simulated and verified through analysis. Experimental results on a 0.5kW fuel cell system connected to a utility grid are discussed.

Keywords: anti-islanding, distributed power generation, renewable energy system

1. Introduction

Utility-interactive renewable energy systems are likely to become a small, but important source of electric generation in the next century. This is a new concept in utility power production, referred to as the distributed power generation system (DPGS). Fig. 1 shows the typical DPGS connected to a utility grid [1]. However, interconnection of the DPGS with the utility raises several major issues and technical difficulties. Islanding is a significant issue of concern as more and more independently controlled DPGSs are connected to the power distribution system. The islanding phenomenon occurs when a utility is intentionally or accidentally disconnected from the network and the DPGS continues to energize local loads. This condition endangers the maintenance personnel arriving to service the energized isolated feeder [2]. Furthermore, unsynchronized re-closing of the utility in forming isolated loads results in damage to fuel cell inverters. This concern is addressed in *IEEE Standard 929-2000* and *IEEE P1547* [3-4].

Several islanding detection algorithms have been developed over the past decade [5-9]. These algorithms can be categorized into two major approaches:

Passive:

- Over/under voltage and frequency detection [5]
- Phase jump detection [5]
- Voltage harmonic monitoring [6]

Active:

- Output power variation [7]
- Active frequency drift [8-9]
- Sliding mode frequency shift [8]

In the over/under voltage and frequency detection approach, the inverter is shut down when the utility voltage/frequency deviates from the set values. While the method is simple, it fails to detect islanding when the inverter generating power closely matches the connected loads [10]. In the phase jump detection method the phase of the inverter current is instantaneously synchronized at zero crossing with the phase of the voltage via phase lock loop (PLL) circuitry. A considerable phase difference can be identified as an occurrence of islanding. However, this method fails when the load power factor is in unity [10].

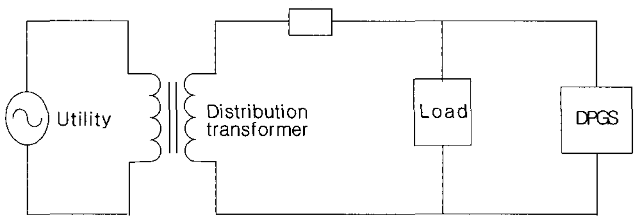

Fig. 1 Utility interconnection diagram of the DPGS

In the voltage harmonic monitoring method, it is envisioned that the absence of the utility (i.e. islanding)

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results in excessive harmonic voltage due to the magnetizing current drawn by power transformers, etc. [2, 10]. However, setting an appropriate harmonic threshold to disconnect the inverter is nearly impossible due to the presence of nonlinear loads. This renders the harmonic monitoring method as impractical [6].

Active methods attempt to overcome the shortcomings of passive methods by introducing perturbations in the inverter output. In the output power variation method the inverter real power is periodically perturbed and the voltage is continuously monitored. When islanding occurs, voltage fluctuations become apparent due to real power mismatch. This information is used to initiate the shut down procedure. This process requires the synchronization of the multiple DPGS's connected to the utility. If synchronization is not performed, the method becomes ineffective due to the averaging effect [7]. The active frequency drift (AFD) method introduces a small increase/decrease in the frequency of the inverter output current while monitoring the frequency of the voltage. A measurable deviation in frequency of the voltage indicates islanding. However, this method has been shown to fail when the load phase angle matches with the phase offset generated by perturbing the frequency [8]. The sliding mode frequency shift (SMS) method applies a similar strategy as that used in AFD. In this technique the starting angle of the inverter current is controlled. Under islanding a measurable frequency deviation is observed. This method also fails when the load phase angle equals the starting angle [8].

In response to these concerns, this paper explores the development of a robust anti-islanding algorithm. The proposed algorithm continuously perturbs (±5%) the reactive power supplied by the DPGS while monitoring the utility voltage and frequency. It is shown that by perturbing the reactive power of the DPGS by ±5%, observable frequency deviation (> ±1%) results when islanding occurs. To further positively confirm islanding the proposed algorithm reduces the DPGS real power output to 80%. Now if the terminal voltage drops below 0.9 pu, the DPGS is disconnected. This method of detection is shown to be robust, fast acting (operable in one cycle) and significantly reduces the non-detection zone (NDZ) compared to all other detection methods. Several possible islanding conditions are simulated and verified through investigation. Experimental results on a 0.5kW distributed fuel cell powered generation (DFPG) connected to a utility grid are discussed.

2. Analysis of Real and Reactive Power Mismatch

Islanding voltage and frequency can be calculated analytically based on real and reactive power mismatch at the instant the utility is disconnected. Fig. 2 (a) shows the power flow diagram of distributed fuel cell powered generation (DFPG) and connected load in the presence of the utility. Fig. 2 (b) presents the utility that is disconnected and ΔP and ΔQ are defined as real and reactive power mismatches at the instant of disconnection.

For the purpose of analysis, DFPG is modeled as a current source and the load is represented by equivalent parallel RLC elements. Per phase equivalent circuit of the system for this condition is depicted in Fig. 3.

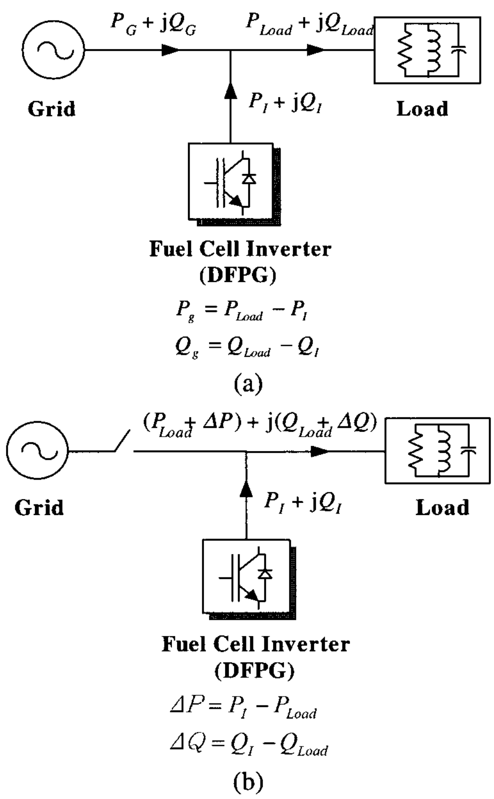


Fig. 2 Interconnection of DFPG source to the utility and the load (a) Normal condition (b) Under islanding

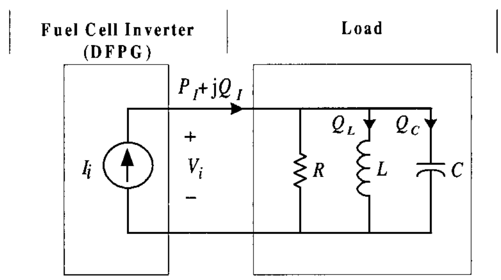


Fig. 3 Equivalent circuit of the DFPG and the load at the instance the utility is disconnected

For clarity, the term "*islanding voltage* V_i " is defined as the voltage at inverter terminal and the load terminals. The term "*islanding frequency*" is defined as the frequency of inverter output when the utility is disconnected.

Let:
P_I : Real power output of the DFPG
Q_I : Reactive power output of DFPG
P_G: Real power output of the utility
Q_G: Reactive power output of the utility
Q_C: Capacitive reactive power (of the load)
Q_L: Inductive reactive power (of the load)
ΔP: Real power mismatch between DFPG and utility
ΔQ: Reactive power mismatch between DFPG and utility
V_i : Islanding voltage
V : Nominal system voltage

Since the load is represented by equivalent RLC elements and is connected in parallel, islanding voltage across the R and parallel LC are equal. Impedance of parallel LC (Fig. 3) in a function of frequency is expressed as,

$$|Z_{LC}| = \frac{\omega_i L}{1-\omega_i^2 LC} \quad (1)$$

Where, ω_i is the islanding frequency. Further, Z_{LC} can be expressed in terms of P_I and Q_I variables as,

$$|Z_{LC}| = \frac{R \cdot P_I}{Q_I} \quad (2)$$

Equating (1) and (2) we obtain,

$$\omega_i^2 - \frac{Q_I}{RCP_I}\omega_i - \left(\frac{1}{\sqrt{LC}}\right)^2 = 0 \quad (3)$$

The quality factor, q of the connected load is defined as [1],

$$q = \frac{\sqrt{|Q_L| \cdot |Q_C|}}{P} = R\sqrt{\frac{C}{L}} \quad (4)$$

Equation (3) can be expressed in terms of q as,

$$\omega_i^2 - \frac{R}{q^2 L}\frac{Q_I}{P_I}\omega_i - \left(\frac{R}{qL}\right)^2 = 0 \quad (5)$$

From (5), the islanding frequency ω_i can be computed,

$$\omega_i \approx \frac{1}{\sqrt{LC}} \cdot \left(\frac{1}{2}\frac{Q_I}{qP_I} + 1\right) \quad (6)$$

Voltage at the moment the utility is disconnected (islanding voltage) can be calculated from the following equation,

$$\frac{V_I}{V} = \sqrt{\frac{P_I}{P_{Load}}} \quad (7)$$

The islanding voltage, V_i can be expressed as,

$$V_i = \sqrt{k} \cdot V \quad (8)$$

Where,

$$k = \sqrt{\frac{P_I}{P_{Load}}} \quad (9)$$

From the above analysis the following can be concluded:

- The islanding frequency, ω_i is a function of DFPG real power (P_I), reactive power (Q_I) and the resonant frequency of the load ($1/\sqrt{LC}$) as shown in (6).
- Voltage at the inverter terminals at the instant the utility is disconnected is a function of the ratio of real power of the DFPG and the load as shown in (8).
- Islanding voltage V_i increases when $P_I > P_L$ and decrease and vice versa.
- The worst case condition occurs in the following scenario: when DFPG real power is equal to the real power of the load, i.e. $P_I = P_{Load}$ and the corresponding reactive powers are also equal, $Q_I = Q_{Load}$. For this condition the voltage and the frequency at the inverter terminals continues to be the same as when the utility was connected. Under this condition the inverter fails to notice the disconnection of the utility and continues to operate, hence causing islanding. When the above described conditions are not nearly met, the variation in voltage and frequency may be small and may escape detection. This zone is called the non- detect zone (NDZ).

3. A Robust Anti-Islanding Algorithm Development

To detect islanding effectively, it is necessary to have a good understanding of all possible islanding conditions. Three major islanding scenarios are explored and a robust anti-islanding algorithm is developed and presented in this section.

Case # 1: ΔP is large:

When the real power of DFPG and that of the load are not equal, ΔP is large. Under these conditions if the utility is disconnected, then from (8) it is clear that the inverter terminal voltage will vary widely. Fig. 4 shows the variation of the islanding voltage V_i as a function of ΔP. According to the IEEE Standard 929-2000 [3], the inverter operating voltage should be within the range of $0.88 \le V_i \le 1.10$ pu. If these operating limits are chosen, the islanding condition can be detected effectively only if $\Delta P > \pm 20\%$ (Fig. 4).

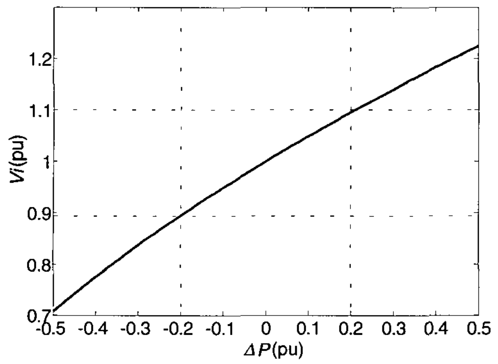
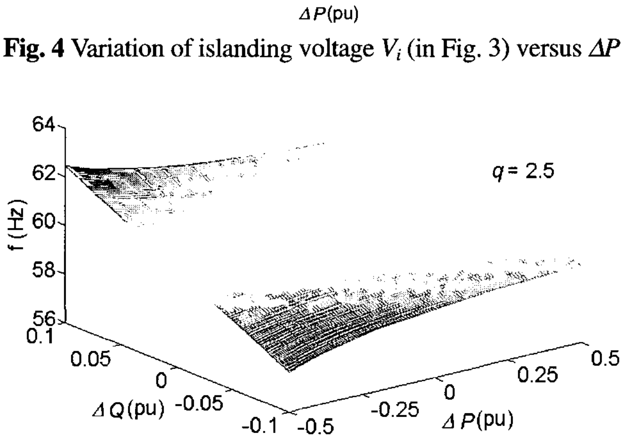
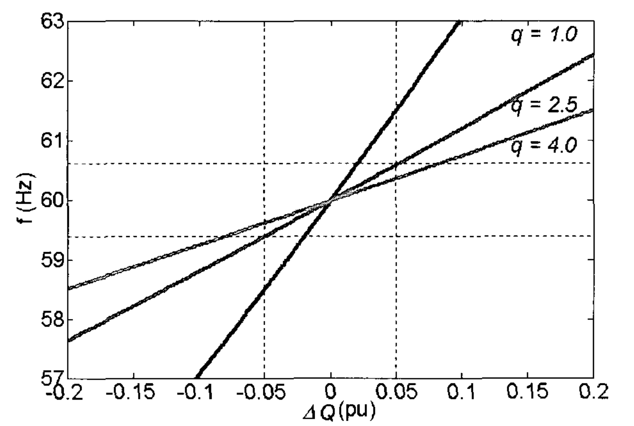


Fig. 4 Variation of islanding voltage V_i (in Fig. 3) versus ΔP



(a)



(b)

Fig. 5 (a) Variation of islanding frequency (in Fig. 2) as a function of ΔP and ΔQ variables for q = 2.5 (b) frequency vs. ΔQ as a function of q when $\Delta P \approx 0$

Case # 2: ΔP is small and ΔQ is large:

In this case, the real power of DFPG and the load are nearly equal (i.e. ΔP is small), however, the reactive power of DFPG and the load differ (ΔQ difference is larger). Upon disconnection of the utility, the relationship derived in (6) confirms that a change in frequency occurs. Fig. 5 (a) shows variation of the islanding frequency as a function of ΔP and ΔQ. Fig. 5 (b) shows islanding frequency variation as a function of ΔQ when ΔP is zero. It is noted that the variation is also a function of the quality factor q of the load (see (6)). According to the IEEE, Standard 929-2000 [3], the inverter operating frequency should be within the range of 59.3Hz to 60.5Hz. Therefore, the DFPG must disconnect when the frequency is out of these limits. However, if this condition is chosen for islanding protection, the inverter (DFPG) will fail to disconnect when the load q = 2.5, ΔP = 0, and $\Delta Q < \pm 5\%$ (see Fig. 5 (b)).

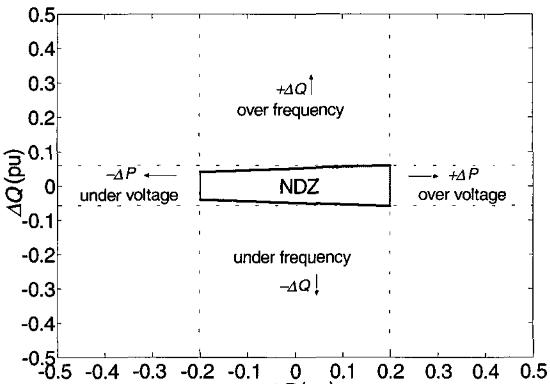


Fig. 6 Existence of non-detection zone (NDZ) of over/ under voltage and frequency method

Case # 3: ΔP and ΔQ are small:

It is clear from Case # 1 and # 2 analysis that a small ΔP (< ±20%) results in an insufficient change in voltage V_i (Fig. 4) and a small ΔQ (< ±5%) results in inadequate change in frequency (Fig. 5) to effectively disconnect the DFPG and prevent islanding. This zone is commonly known as the non-detection zone (NDZ) for the passive methods to detect islanding and is illustrated in Fig. 6. The focus of the proposed algorithm in this paper is to reduce the NDZ to nearly zero and this is detailed in the next section.

4. Proposed Power Control Algorithm

The focus of the proposed algorithm is to reduce the NDZ to almost zero. The algorithm consists of two steps. In step #1, the reactive power (Q_l) of the DFPG is continuously perturbed by ±5%, while maintaining the real power (P_l) constant. Both the voltage and frequency are monitored simultaneously. Now the ratio of Q_l to P_l is expressed as,

$$\frac{Q_l}{P_l} = K \cdot \mathrm{sgn}(V_i) \tag{10}$$

Where K denotes the reactive power perturbation and is set to 5% (or 0.05 per-unit). For this setting a noticeable frequency deviation can be observed during the load q <

2.5 (see Fig. 5). From (6), the islanding frequency for this perturbation can be calculated as,

$$\omega_i = \frac{1}{\sqrt{LC}}\left(\frac{K \cdot \mathrm{sgn}(V_i)}{2q} + 1\right) \tag{11}$$

The frequency deviation ($\Delta\omega_i$) is defined as.

$$\Delta\omega_i = \omega_{i[k]} - \omega_{i[k-1]} \tag{12}$$

When the utility is connected, the frequency deviation $\Delta\omega_i$ is small or nearly zero. However, the instant the utility is disconnected, a change in $\Delta\omega_i$ is noticeable due to ±5% perturbation in Q_I. When the change in $\pm 1\% \le \Delta\omega_i \le \pm 2\%$, the possibility of islanding occurrence is considered to be somewhat higher since it is within the specified limit of IEEE Standard 929-2000 [3], (59.3Hz to 60.5Hz). This change is observed for at least four consecutive cycles. If during this period the frequency fluctuation increases rapidly, then islanding is confirmed and the DFPG is disconnected. However, if $\Delta\omega_i$ continues to be within the above specified limits, the proposed algorithm reduces the DFPG real power to 80% (i.e. 0.8 per-unit) for another 10 cycles as apart of step #2. Now if the magnitude of the voltage V_i falls below 0.9 per-unit, the occurrence of islanding is confirmed and the DFPG is disconnected. In case the magnitude of the voltage V_i is normal the DFPG is allowed to continue its operation. The proposed two step approach, (described above), is robust and fast acting. Fig. 7 shows a flowchart of the proposed robust anti-islanding algorithm.

5. Simulation

In this section simulation results are presented to illustrate the effectiveness of the proposed anti-islanding algorithm. Three possible islanding cases are simulated. The DFPG is represented by a voltage controlled current source and its frequency is monitored every half cycle by an integrator that can be reset. Table 1 indicates the parameters used in the simulation of the system. Real and reactive power mismatches (ΔP, and ΔQ) are defined in Table 2 and also in Chapter 2.

Table 1 Simulation parameters

Parameters	Value
Voltage	220 V
Frequency	60 Hz
P_{Load}	0.5 kW, 28.80 Ω
Q_L	1.25 kVAR, 30.56mH
Q_C	1.25 kVAR, 230.25μF

In Fig. 8, for case # 1: real power mismatch between DFPG and the loads is large (ΔP = -0.5 per-unit and ΔQ = 0 per-unit). Under normal conditions the DFPG continuously supplies constant real power (P_I = 0.5 per-unit, Q_I = 0 per-unit) to the load. At the instant the load is disconnected, the magnitude of the voltage V_i immediately drops to 0.70 per-unit (Fig. 8a) due to insufficient real power supplied from the DFPG (see(8)). The occurrence of islanding can be easily detected by monitoring the under voltage. It is noted that the frequency does not alter significantly since ΔQ is zero.

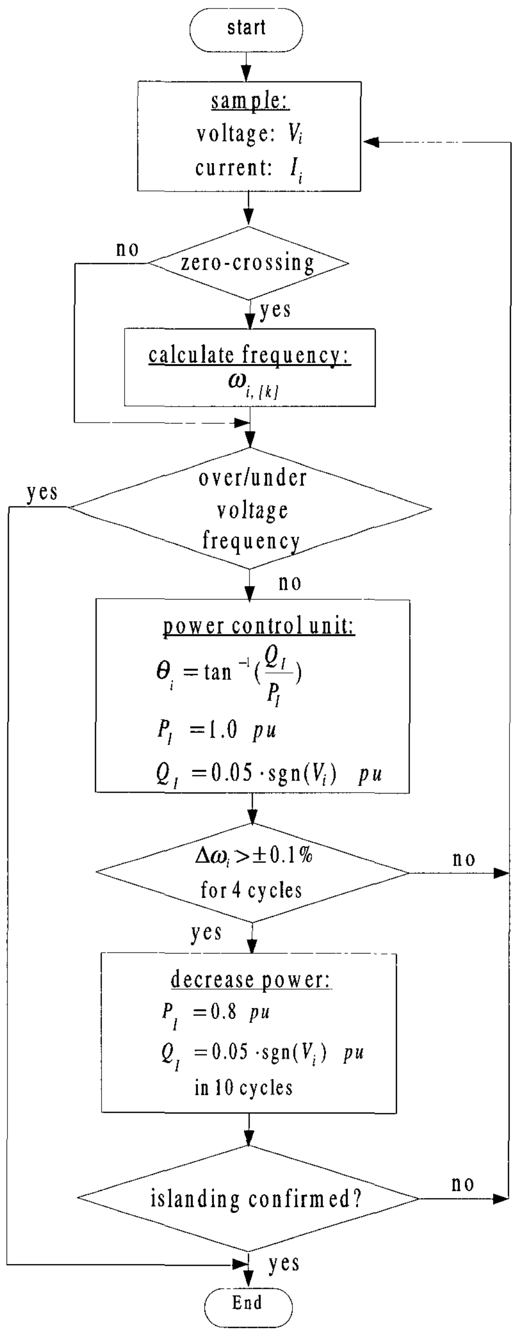
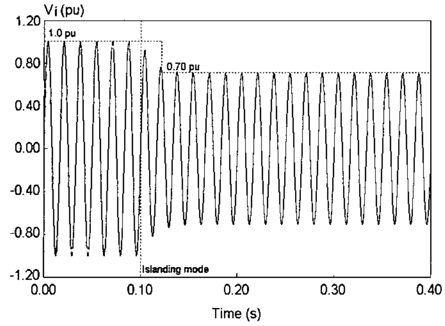


Fig. 7 A robust anti-islanding detection algorithm



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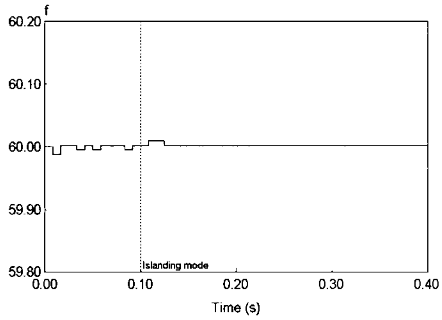
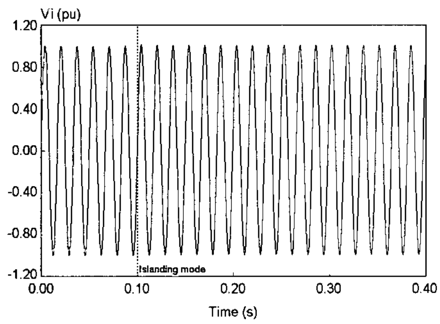


(b)

Fig. 8 Simulation results for Case # 1: ΔP is large, (b) islanding frequency of ΔP = -0.5 and ΔQ = 0.



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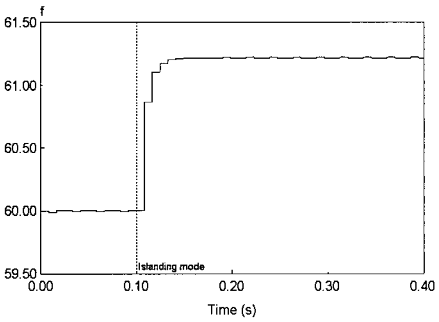
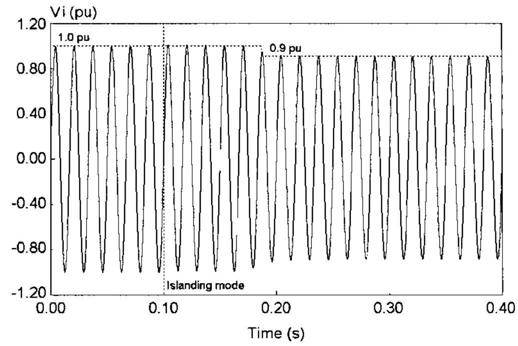


(b)

Fig. 9 Simulation results for case #2: ΔP is small and ΔQ is large (a) islanding voltage and (b) islanding frequency of ΔP = 0 and ΔQ = -0.1



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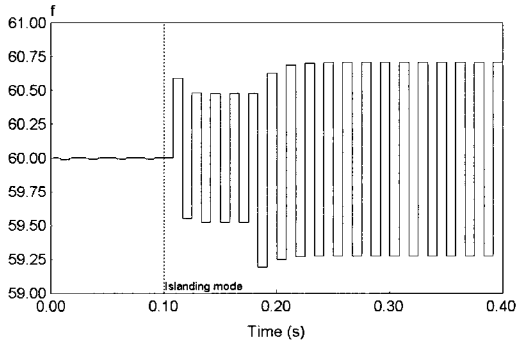

(b)

Fig. 10 Simulation results for case #3: ΔP and ΔQ are small and a robust anti-islanding algorithm is applied (a) islanding voltage and (b) islanding frequency of $\Delta P \approx 0$ and $\Delta Q \approx 0$

Fig. 9 presents the simulation results for Case # 2: for ΔP = 0 and ΔQ = 0.1 per unit. In this case, the DFPG real power P_I is identical to load P_{Load} , however the DFPG reactive power Q_I exceeds Q_{Load} by 0.1 per unit. The magnitude of V_i remains unaltered at the instant the utility is disconnected, however the frequency increases to 61.2 Hz. This new operating frequency results from a larger reactive power mismatch (see (6)). Since this exceeds the IEEE 929-2000 [3] specified limit (59.3Hz to 60.5Hz), the islanding condition is positively confirmed.

Fig. 10 indicates the simulation results for Case #3: both the real and reactive power mismatches are small ($\Delta P \approx 0$ per unit and $\Delta Q \approx 0$). For this condition to exist, the DFPG real and reactive power must match the connected load. That is $P_I \approx P_{Load}$ and $Q_I \approx Q_{Load}$). From the previous analysis it is clear that this is the most difficult scenario in which to detect islanding. The proposed robust anti-islanding algorithm is employed. In this case the DFPG real power is maintained constant and its reactive power is perturbed by ±5%. At the instant the utility is disconnected, from Fig. 10(b) it is noted that a frequency deviation is observed ($\Delta\omega$ = ± 0.8Hz). According to the proposed algorithm the DFPG is allowed to continue its operation as long as frequency variation is within the specified limit (59.3Hz to 60.5Hz). In the mean time, the algorithm recognizes the frequency variation for over four consecutive cycles and the DFPG real power P_I is then reduced to an 80% level for the next 10 cycles. It is noted in Fig. 10(a) that the terminal voltage magnitude (V_i) is reduced to 0.9 per unit, thus positively confirming islanding.

6. Experimental Results

Fig. 11 illustrates the experimental setup of a single phase fuel cell inverter rated at 0.5kW, 120V and 60Hz connected to the utility. The inverter is controlled in current control mode employing a TMS-320-F243 digital signal processor (DSP). The proposed robust anti-islanding algorithm is implemented in DSP via software. Under normal condition, the inverter (DFPG) is programmed to

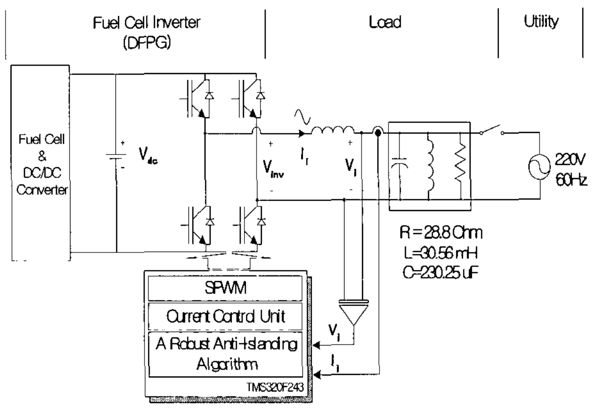

Fig. 11 Experimental set up

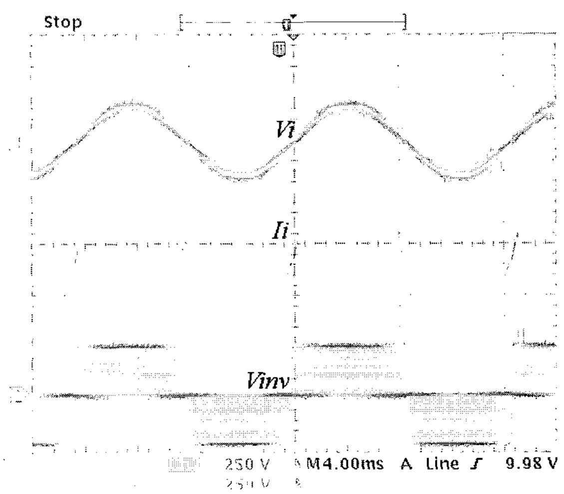

Fig. 12 Experimental result of normal operation of the DFPG connected to the utility, CH2: fuel cell inverter voltage (V_{inv}) 500V/div, CH3: fuel cell inverter current (I_i) 4A/div, CH4 terminal voltage (utility voltage, V_i), 500V/div.

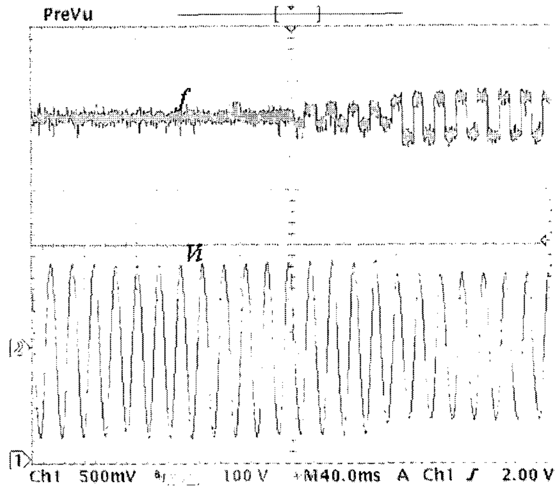

Fig. 13 Experimental result of islanding detection by the developed robust anti-islanding algorithm, CH1: frequency of terminal voltage 2.65 ms/div, CH2: terminal voltage (islanding, voltage, V_i), 200V/div.

continuously supply the available fuel cell power to the utility. The reactivity of the inverter is constantly perturbed by ±5% as described in the previous sections. Both real and reactive power supplied by the DPFG can be controlled by altering the phase shift between utility voltage and inverter current. Fig. 12 shows the normal operation of the DFPG when connected to the utility. Fig. 13 depicts the noticeable frequency deviation ($\Delta\omega$ = ±0.95) when islanding occurs for Case #3. The inverter (DFPG) continues to operate (Fig. 13) for four cycles and initiates the real power reduction to 0.8 per unit, upon which the voltage (V_i) is reduced. Consequently, islanding is confirmed.

7. Conclusion

In this paper a robust anti-islanding algorithm for utility interconnection of distributed fuel cell power generation (DFPG) has been presented. It has been shown via analysis that the islanding voltage depends on real power mismatch alone and the islanding frequency is a function of both real and reactive power. The robust anti-islanding algorithm has been fully analyzed and simulation and experimental results confirm the effectiveness of the proposed method.

Acknowledgements

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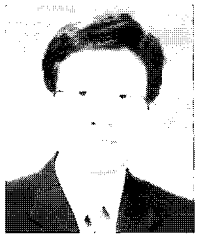

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