An Improved Anti-Islanding Algorithm for Utility Interconnection of Multiple Distributed Fuel Cell Powered Generations

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Abstract - This paper presents an improved anti-islanding algorithm for utility interconnection of multiple distributed fuel cell powered generations (DFPGs). A cross-correlation method is proposed and implemented in conjunction with the anti-islanding algorithm developed in the previous work [1]. While the power control algorithm continuously perturbs (±5%) the reactive power supplied by the DFPG, the proposed algorithm calculates the cross-correlation index of a rate of change of the frequency deviation with respect to (±5%) the reactive power to confirm islanding. If this index is above 50%, the algorithm further initiates (±10%) the reactive power perturbation and continues to calculate the correlation index. If the index exceeds 80%, the occurrence of islanding can be confirmed. The proposed method is robust and capable of detecting the occurrence of islanding in the presence of several DFPGs, which are independently operating. Viability of the cross-correlation method is verified by the simulation. Experimental results are presented to support the findings of the proposed method.

Keywords: anti-islanding algorithm, utility interconnection, DFPG

1. Introduction

Detecting an occurrence of islanding when a number of (small & large) distributed fuel cell powered generations (DFPGs) are connected to the utility has always been a challenge. In the previous work [1], the anti-islanding algorithm for utility interconnection of distributed fuel cell powered generations has been developed. The power control algorithm continuously perturbs (±5%) the reactive power supplied by the DFPG, while simul-taneously monitoring the voltage at inverter terminals and the frequency. In most cases, islanding can be confirmed by detecting over/under voltage and/or frequency ($0.88 < V_i < 1.10$ per-unit and $59.3 < \omega_i < 60.5$ Hz) [2-3]. However, under the worst case islanding condition, the occurrence of islanding is firstly noticed when the frequency deviation ($\Delta\omega > 1\%$) is observed for four consecutive cycles. In the following step, the output real power is immediately dropped to 80%. If the terminal voltage drops lower than the threshold ($V_i < 0.88$ per-unit), islanding can be positively confirmed. This method of detection has been shown to be robust, fast acting (operable in a few cycles), and capable of reducing the size of a non-detection zone (NDZ) to zero. However, it can possibly fail to detect islanding when several (small & large) DFPGs are independently operating in parallel to the utility as shown in Fig. 1. The cause of the failure stems from dilution of (±5%) the reactive power perturbation and the drop in the real power due to averaging effects [4]. Thus, it results in insufficient frequency deviation and/or voltage drop to confirm islanding.

As a result, the improved anti-islanding algorithm for utility interconnection of multiple DFPGs is explored. Islanding voltage and frequency are analyzed based on real and reactive power mismatches. Following the analysis, the cross-correlation method is proposed and implemented in conjunction with the anti-islanding algorithm developed in the previous work [1]. While the power control algorithm continuously perturbs (±5%) the reactive power supplied by the DFPG and monitors the voltage and the frequency, the cross-correlation index of a rate of change of the frequency deviation ($\Delta\omega$) with respect to (±5%) the reactive power perturbation is calculated. It is used to confirm the occurrence of islanding. In the presence of the utility, the voltage at inverter (DFPG) terminals and the frequency reside in the threshold ($0.88 < V_i < 1.10$ per-unit and $59.3 < \omega_i < 60.5$ Hz). Furthermore, the cross-correlation index is nearly zero ($c \approx 0$). If islanding were to occur, this index rapidly increases above 50% ($c > 0.5$). To

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further confirm islanding, the proposed algorithm initiates (±10%) the reactive power perturbation and continues to calculate the cross-correlation index c. If this index increases higher than 80% ($c > 0.8$), the occurrence of islanding can be positively confirmed. The proposed cross-correlation method is shown to be a viable technique to detect islanding in the presence of several DFPGs, which are independently operating. Viability of the cross-correlation method is verified by the simulation. Experimental results further confirm the effectiveness of the proposed method.

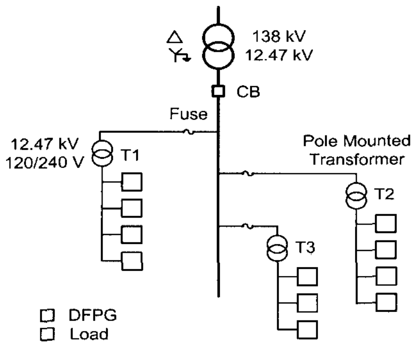


Fig. 1 Multiple DFPGs independently operates in parallel with the utility

2. Analysis of Islanding Voltage and Frequency

Fig. 2 (a) shows an equivalent circuit of multiple DFPGs, which are connected in parallel to the RLC load and the utility. Each of DFPGs independently operates. They regulate sinusoidal waveform currents impressed into the utility grid. Thus, they can be represented as ideal current sources. It is assumed that the resistive load (R) and the reactive load (LC) consume real and reactive power respectively.

Fig. 2 (b) shows a simplified equivalent circuit. The DFPG #2-4 and the RLC load are reformed as an equivalent islanding load. With this arrangement, the DFPG #1 can be realized as a single inverter (DFPG) connected to the equivalent islanding load. Therefore, analysis of islanding voltage and frequency based on real and reactive power mismatches ΔP and ΔQ in the previous work [1] can be applied.

In the analysis, it is assumed that the occurrence of islanding is the worst case, which holds the following assumptions

- Real and reactive power mismatches between the DFPGs and the RLC load are zero ($\Delta P = 0, \Delta Q = 0$)
- Resonant frequency of the RLC load is equal to the system frequency (60 Hz)
- Reactive power of the RLC load is zero ($Q_{LC} = 0$)

Let:

. P_I : Sum of real power from all DFPGs
Q_I : Sum of reactive power from all DFPGs
$P_{I,i}$: Real power supplied from DFPGs ($i = 1...N$)
$Q_{I,i}$: Reactive power supplied from DFPGs ($i = 1...N$)
P_S : Real power supplied by the utility
Q_S : Reactive power supplied by the utility
P_R : Load real power
Q_{LC} : Load reactive power
P : Real power mismatch ($\Delta P =$. $P_I - P_R$)
Q : Reactive power mismatch ($\Delta Q =$. $Q_I - Q_{LC}$)
V_i : Inverter terminal voltage
V_n : Nominal system voltage
ω_i : Frequency of the inverter terminal voltage
ω_r : Load resonant frequency $1/\sqrt{LC}$
q : Load quality factor ($R/\sqrt{C/L}$)
k : Generation to load ratio ($k = P_{I,i} / P_R$)

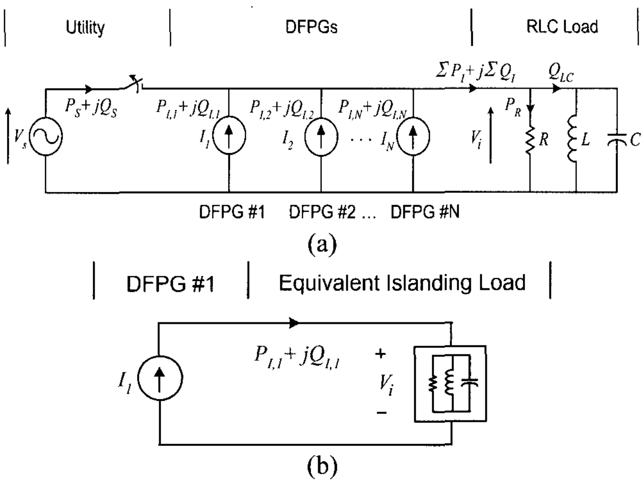


Fig. 2 (a) Full description of an equivalent circuit of islanding, (b) A simplified equivalent circuit of islanding

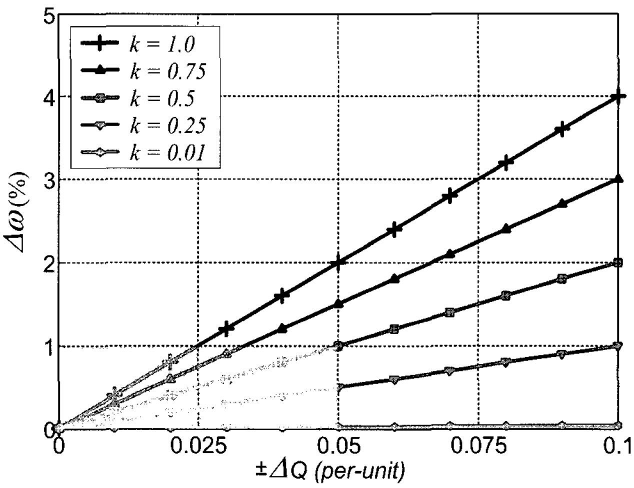


Fig. 3 Frequency deviation versus $\Delta Q_{I,1}$

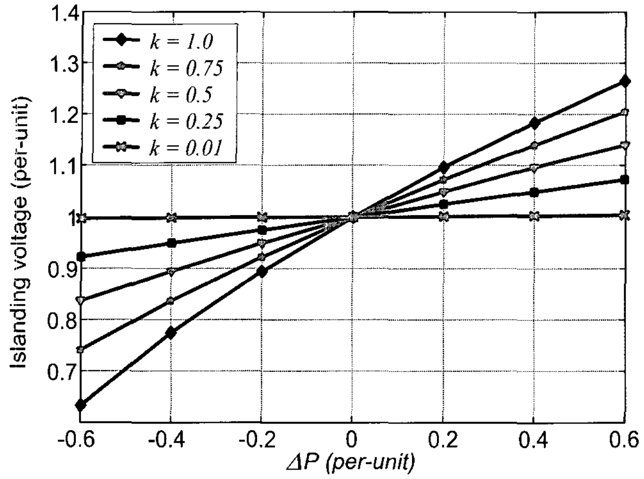


Fig. 4 Islanding voltage versus $\Delta P_{I,1}$

After disconnection of the utility, islanding voltage V_i is expressed in per-unit as, (see derivation in appendix)

$$\frac{V_i}{V_n} = \sqrt{k\cdot\left(\frac{\Delta P_{I,1}}{P^0_{I,1}}\right)+1} \tag{1}$$

and

$$P_{I,1} = P^0_{I,1} + \Delta P_{I,1} \tag{2}$$

where $P_{I,1}$ denotes real power supplied from the DFPG #1, $P^0_{I,1}$ denotes real power in the steady state, and $\Delta P_{I,1}$ denotes real power perturbation.

Frequency deviation $\Delta\omega$ can be expressed as, (see derivation in appendix)

$$\frac{\Delta\omega}{\omega_r} \approx \frac{1}{2q}\cdot\left(\frac{\frac{\Delta Q_{I,1}}{P^0_{I,1}}}{\frac{\Delta P_{I,1}}{P^0_{I,1}}+\frac{1}{k}}\right) \tag{3}$$

And

$$Q_{I,1} = Q^0_{I,1} + \Delta Q_{I,1} \tag{4}$$

where $Q_{I,1}$ denotes reactive power supplied from the DFPG #1, $Q^0_{I,1}$ denotes reactive power in the steady state, and $\Delta Q_{I,1}$ denotes reactive power perturbation.

According to the analysis (3), frequency deviation $\Delta\omega$ becomes less than 1% when the DFPG #1 supplies power less than half of the load real power (or a generation to load ratio $k < 0.5$) as shown in Fig. 3 (in the shaded area). Therefore, the anti-islanding algorithm developed in [1] cannot recognize the occurrence of islanding. In addition, the analysis in (1) shows that a drop in the output real power (P_I = 80%) to positively confirm islanding is also ineffective due to insufficient real power reduction as shown in Fig. 4.

To detect the occurrence of islanding effectively, the DFPG #1 and other DFPGs connected to the utility should have been synchronized. Thus, real and reactive power exported from each unit are controlled in the same direction which allows the presence of at least 20% real power mismatch and ±5% reactive power mismatch taking place after disconnection of the utility. However, this ideal solution could not happen. Thus, the cross-correlation method is proposed to improve the effectiveness of the anti-islanding algorithm developed in the previous work [1]. Fundamental of the cross-correlation function and the proposed algorithm are detailed in the following sections.

3. Cross-Correlation Function

The cross-correlation function is a measure of the similarity between two signals. Thus, it can be used to evaluate relationship of the frequency deviation occurred in response to the reactive power perturbation. Mathematical expression of the cross-correlation function between the frequency deviation $\Delta\omega$ and the (±5%) reactive power perturbation in discrete-time is expressed as,

$$c_{[n]} = \frac{1}{K}\left(\frac{1}{M}\sum_{m=0}^{M}\left(\frac{\Delta\omega_{[m]}}{\Delta Q_{I[n+m]}}\right)\right) \tag{5}$$

and

$$K = \frac{k\omega_r}{2q} \tag{6}$$

where M is an order (filter length) of the cross-correlation function, K is a normalized constant, and k is a generation to load ratio.

If the frequency deviation $\Delta\omega$ strongly depends on (±5%) the reactive power perturbation ΔQ_I , the cross correlation index will significantly increases near to 100%. However, if those two variables have no relationship, the crosscorrelation index is considerably less than 100%. The latter condition can occur only when DFPGs are connected to the utility.

Fig 5 shows calculation of the cross-correlation index. It is noticed that at lagging time n = 6, the frequency deviation $\Delta\omega$ perfectly correlates with the reactive power

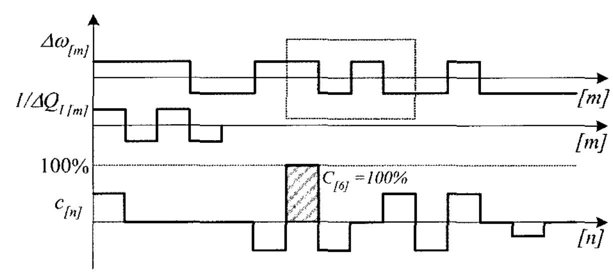


Fig. 5 Illustration of cross correlation index calculation

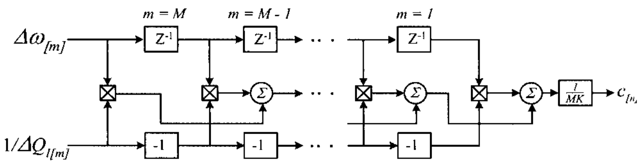


Fig. 6 Discrete-time realization of the cross-correlation function

perturbation $1/\Delta Q_I$. Thus, it results in a significant increase of the cross-correlation index ($c_{[6]}$ = 100%). Discrete-time realization of the cross-correlation function (6) is shown Fig. 6. It can be implemented by software with any digital signal processors similarly to a finite impulse response filter (FIR).

It is important to note here that the order of the cross-correlation function can be chosen up to 240, at this point of which sets the maximum detection time equal to the maximum islanding time (2 sec) [2-3]. The cross-correlation threshold to confirm islanding can be selected between 70%-90%. However, choosing the lower threshold can result in nuisance tripping of DFPGs. In contrast, the higher threshold can cause the proposed method less effective.

4. Proposed Cross-Correlation Method

The proposed cross-correlation method is implemented in conjunction with the anti-islanding algorithm in the previous work [1]. That is, the power control algorithm constantly supplies (100%) the real power and (±5%) the reactive power given by (7) and (8), while simultaneously monitoring the voltage at inverter (DFPG) terminals and the frequency. In addition, the proposed method calculates the cross-correlation index of a rate of change of the frequency deviation $\Delta\omega$ with respect to (±5%) the reactive power perturbation ΔQ_I supplied by the DFPG.

$$P^0_I = 1.0 \text{ (per-unit)} \quad (7)$$

$$\frac{\Delta Q_I}{P^0_I} = 0.05 \cdot sign(V_i) \text{ (per-unit)} \quad (8)$$

Thus, islanding can be confirmed, if one of the following three cases is satisfied.

1) If the DFPG terminal voltage or the frequency is out of the threshold $0.88 \le V \le 1.10$ per-unit and $59.3 \le f \le 60.5$ Hz respectively as specified by IEEE Std 929-2000 [2] or IEEE Std 1547-2003 [3], the occurrence of islanding is immediately confirmed.
2) If the DFPG terminal voltage and the frequency remain in the threshold but the frequency deviation is greater than 1% ($\Delta\omega > 1\%$) by four consecutive cycles, the power control algorithm reduces the output real power to 80%. If the DFPG terminal voltage falls below 0.88 per-unit, islanding can be confirmed.
3) If the DFPG terminal voltage and the frequency reside in the threshold and the frequency deviation is less than 1% ($\Delta\omega < 1\%$) but the cross-correlation index is higher than 50%, the proposed method further initiates (±10%) the reactive power perturbation and continues to calculate the cross-correlation index. If the index keeps increasing until it is higher than 80%. The occurrence of islanding can be positively confirmed.

Case #1 and case #2 have been developed as a part of the anti-islanding algorithm developed in [1]. Experimental results have confirmed the effectiveness of the algorithm. In case #3, the proposed cross-correlation method enables a small scale DFPG ($k < 0.50$) to effectively detect islanding in the presence of several DFPGs while independently operating in parallel. Flow chart of the proposed cross-correlation method is shown in Fig. 7.

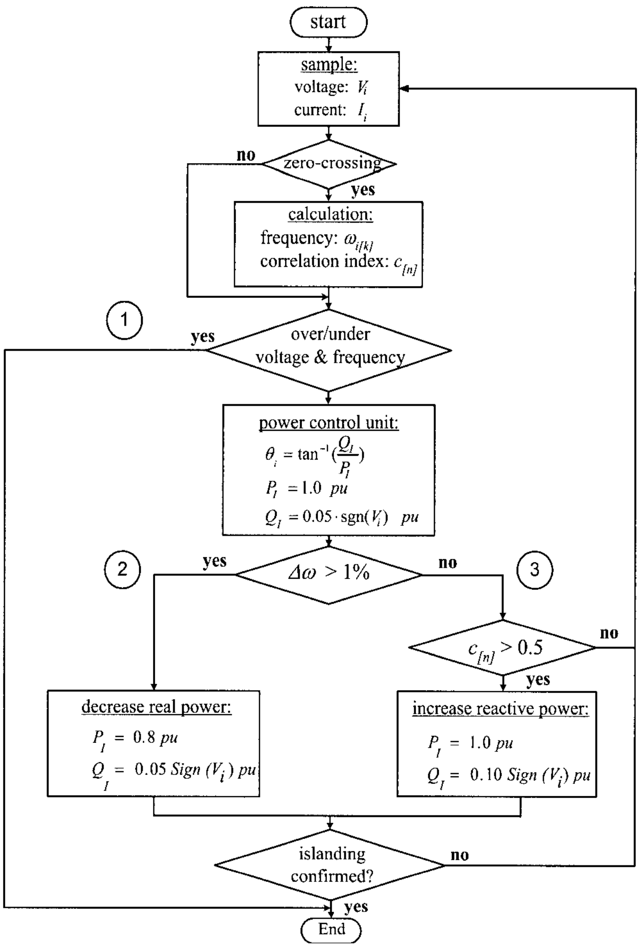


Fig. 7 Flow chart of the proposed cross-correlation method

5. Simulation

To demonstrate viability of the proposed cross-correlation method, the simulation of several DFPGs independently operating in parallel is tested under the worst case islanding condition. Fig. 8 shows a circuit diagram of the simulation. The proposed cross-correlation method is only employed by the DFPG #1. Simulation parameters are shown in Table 1. The (120V/60Hz) utility system is simply modeled by a sinusoidal voltage source. A series resistor-inductor represents a line impedance of the utility grid. All fuel cell inverters (DFPGs) are voltage-source type inverters and operate in current mode while they are synchronized to the utility. Each of them supplies 0.20 kW (0.25 per-unit) real power to the utility. The RLC has load real power rated at 0.8 kW (1.0 per-unit), load quality factor $q = 2.5$ and resonant frequency $\omega_r = 60$Hz. At the instant the utility disconnected, real and reactive power mismatches between the DFPGs and the load are set to nearly zero ($\Delta P \approx 0$ and $\Delta Q \approx 0$).

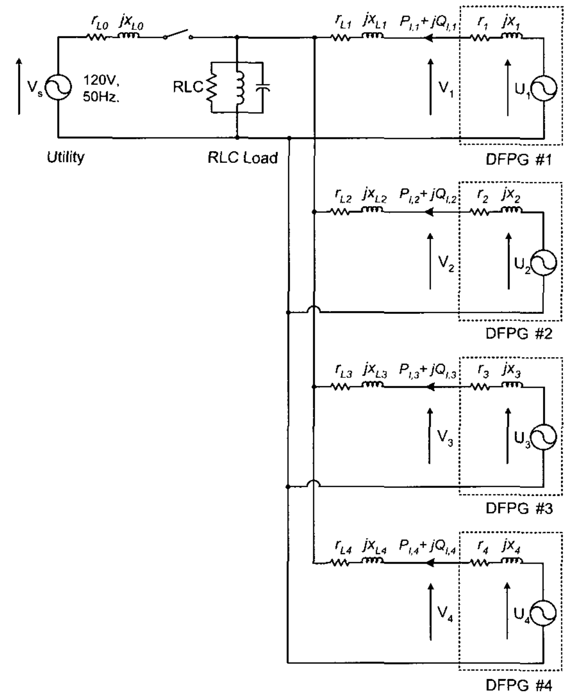


Fig. 8 Simulation circuit

Table 1 Simulation parameters

Parameters	Value
Resistive load (R)	0.8 kW (1.0 per-unit, R = 18 Ω)
Inductive load (L)	2.0 kVAR (L = 19.1 mH)
Capacitive load (C)	2.0 kVAR (C = 368.5 μF)
DFPG #1-4 output power	0.25 (per-unit)
L-Filter	0.05 + j0.377 Ω
Line impedance	0.142 + j0.0574 Ω (per 1000 ft)

Fig. 9 shows simulation results of the proposed method. In the presence of the utility (t < 1.0 sec), the voltage at the DFPG #1 terminals and the frequency are within the threshold ($0.88 < V_i < 1.10$ per-unit and $59.3 < \omega_i < 60.5$ Hz). The cross-correlation index is essentially zero ($c \approx 0$). After the utility is disconnected (t > 1.0 sec), the terminal voltage and the frequency remain in the threshold due to nearly zero real and reactive power mismatches between the DFPGs and the RLC load. Furthermore, the frequency deviation is less than 1% ($\Delta\omega$ < 1%), hence causing the anti-islanding algorithm developed in [1] to be ineffective. However, the cross-correlation index continuously increases as the frequency deviation strongly depends on (±5%) the reactive power perturbation. If the cross-correlation index is higher than 50% (c > 0.50), a chance of islanding is highly possible; upon which the algorithm initiates (±10%) the reactive power perturbation supplied by the DFPG #1 and continues to calculate the cross-correlation index. If the cross-correlation index exceeds 80% (c > 0.80), islanding can be positively confirmed.

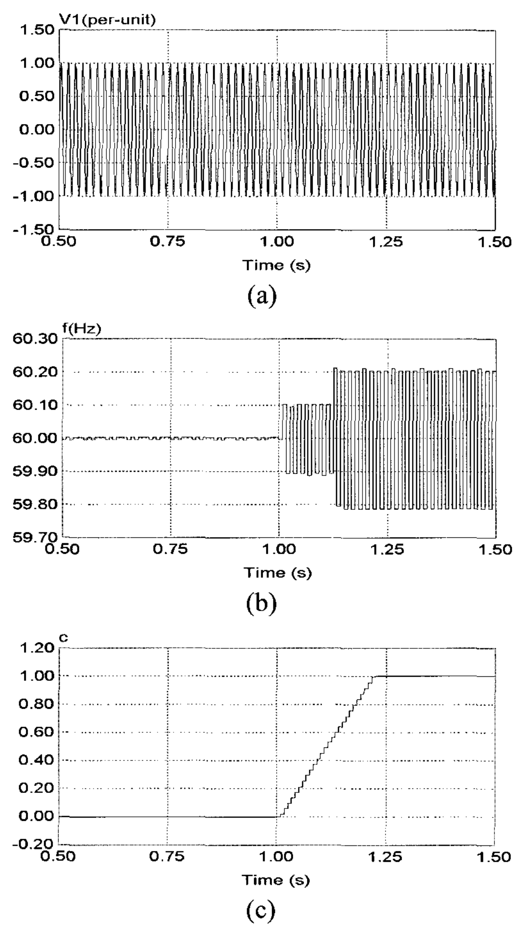


Fig. 9 Simulation results of the proposed method, (a) inverter terminal voltage (per-unit), (b) frequency of the terminal voltage and (c) cross-correlation index $c_{[n]}$

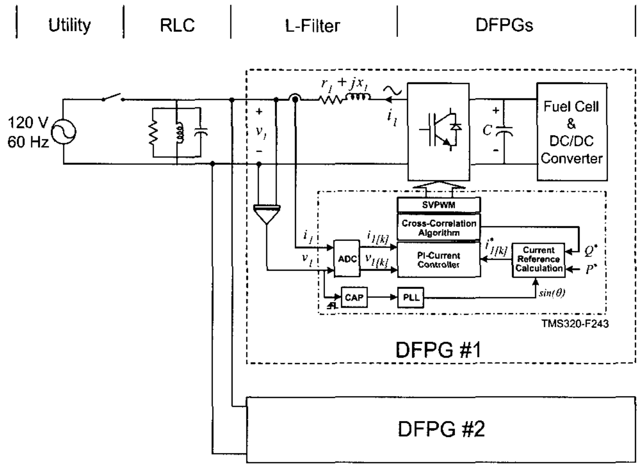
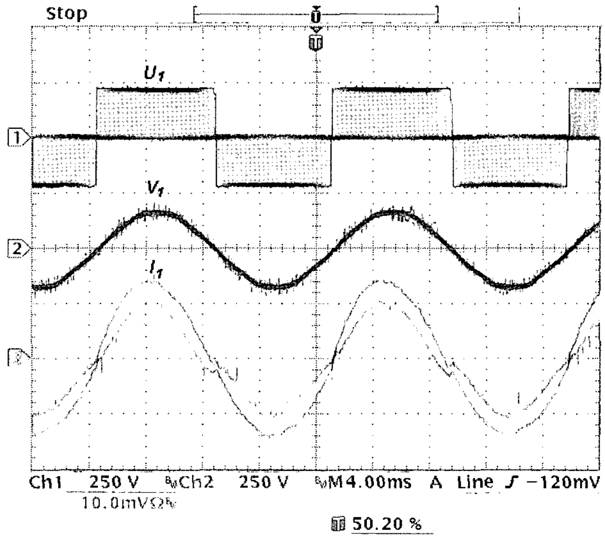


Fig. 10 Experimental setup

6. Experiment

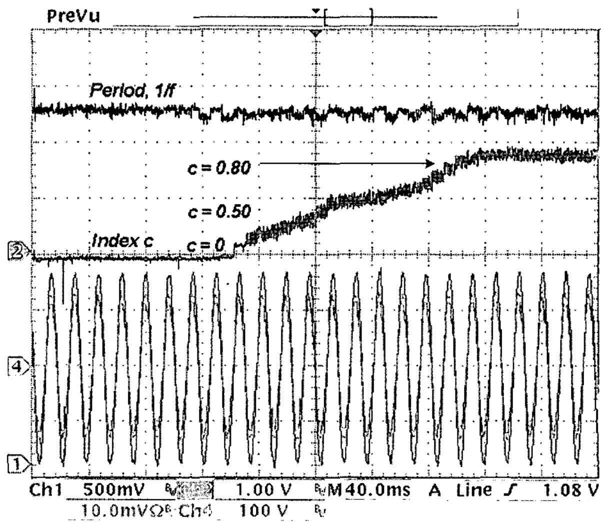
Hardware implementation for testing the proposed cross-correlation method is shown in Fig. 10. The DFPG #1 is rated at 0.20 kW (0.25 per-unit), 120V/60Hz. It is independently operating in parallel with the commercial inverter DFPG #2. This inverter (DFPG #2) has a higher power rating 0.60 kW (0.75 per-unit), representing several other DFPGs (i.e., DFPG #2-4) shown in Fig. 8 as a single unit. The DFPG #1 uses the proposed cross-correlation method. It is implemented in conjunction with the anti-islanding algorithm developed in the previous work [1] in a DSP *TMS320-F243* via software. The DFPG #1 operates in current mode. Under the normal operating condition, the DFPG#1 is programmed to continuously supply the available power from fuel cells to the utility. The reactive power of the DFPG #1 is constantly perturbed by ±5% as described in the previous section. Real and reactive power supplied from the DFPG #1 are controlled by altering the phase shift between the inverter current and the inverter terminal voltage. The RLC load is the same parallel RLC as used in the simulation, which is given in Table 1. Before the utility is disconnected, real and reactive power mismatch between the DFPGs and the RLC load are tuned near to zero.

Fig. 11 shows the inverter switching voltage, the utility voltage, and the inverter current under the normal operating condition, while it is operating in parallel with the utility. In Fig. 12, before disconnection of the utility, the terminal voltage and the frequency reside in the threshold ($0.88 < V_i < 1.10$ per-unit and $59.3 < \omega_i < 60.5$ Hz) and the cross-correlation index is nearly zero. After the utility is disconnected, the terminal voltage and the frequency are still in the threshold. In addition, the frequency deviation ($\Delta\omega < 0.5$ is too small to initiate (80%) the real power reduction and confirm the occurrence of islanding as described in the previous work [1]. However, the cross-correlation index is shown to continuously increase as the frequency deviation strongly correlates with (±5%) the reactive power perturbation. When this index accounts up to 50% (c = 0.50), the proposed method further initiates (±10%) the reactive power perturbation. Now, the larger frequency deviation is observed and the cross-correlation index is higher than 80% (c > 0.80) positively confirming islanding.



CH1: Inverter switching voltage U_I (250V/div),
CH2: Inverter terminal voltage V_I (250V/div),
CH3: Inverter current (2 A/div)

Fig. 11 Experimental result of normal operation of the DFPG #1 connected to the utility



CH1: Period of the inverter terminal voltage (2.625 ms/div)
CH2: Cross-correlation index,
CH3: Inverter current (2 A/div),
CH4: Inverter terminal voltage V_I (250V/div)

Fig. 12 Experimental result of islanding detection by the proposed cross-correlation method

7. Conclusion

In this paper, the improved anti-islanding algorithm for utility interconnection of multiple distributed fuel cell power generations (DFPGs) has been presented. Analysis of islanding voltage and frequency for several DFPGs while independently operating under the worst case islanding condition has been shown. Following to analysis, the cross-correlation method has been proposed and implemented in conjunction with the anti-islanding algorithm, which has been developed in the previous work. This method of detection has been shown to be robust and capable of detecting islanding in the presence of several DFPGs operating independently. Simulation and experimental results have confirmed the effectiveness of the proposed method.

Appendix

As derived in the previous work [1], islanding voltage can be calculated from a ratio of DFPG real power to load real power as,

$$V_i = \sqrt{\frac{\sum_{n=1}^{N} P_{I,n}}{P_R}} \cdot V_n \quad \text{A.1}$$

From Fig. 2, let real and reactive power supplied from the DFPG #1 be expressed as,

$$P_{I,1} = P^0{}_{I,1} + \Delta P_{I,1} \quad \text{A.2}$$

$$Q_{I,1} = Q^0{}_{I,1} + \Delta Q_{I,1} \quad \text{A.3}$$

where $P^0{}_{I,1}$ and $Q^0{}_{I,1}$ denote real and reactive power supplied from the DFPG #1 in the steady state respectively. $\Delta P_{I,1}$ and $\Delta Q_{I,1}$ denote real and reactive power perturbation supplied from the DFPG #1 respectively.

From (A.2), equation (A.1) is rewritten by

$$\frac{V_i}{V_n} = \sqrt{\frac{P^0{}_{I,1} + \Delta P_{I,1} + \sum_{n=2}^{N} P_{I,n} - P_R}{P_R} + 1} \quad \text{A.4}$$

Let real and reactive power mismatches be expressed as,

$$\Delta P = P^0{}_{I,1} + \sum_{n=2}^{N} P_{I,n} - P_R \quad \text{A.5}$$

$$\Delta Q = Q^0{}_{I,1} + \sum_{n=2}^{N} Q_{I,n} - Q_{LC} \quad \text{A.6}$$

Under the worst case islanding condition, real power mismatch is essentially zero $\Delta P \approx 0$. Thus, equation (A.4) is expressed in a function of real power perturbation $\Delta P_{I,1}$ and a capacity ratio ($k = P^0{}_{I,1}/P_R$) as,

$$\frac{V_i}{V_n} = \sqrt{k\frac{\Delta P_{I,1}}{P^0{}_{I,1}} + 1} \quad \text{A.7}$$

Islanding frequency in a function of real and reactive power as derived in the previous work is given in (A.8)

$$\frac{\omega_i}{\omega_r} \approx \left(1 + \frac{1}{2q} \cdot \frac{\sum_{n=1}^{N} Q_{I,n}}{\sum_{n=1}^{N} P_{I,n}}\right) \quad \text{A.8}$$

Let frequency deviation be a difference of frequency between two consecutive half cycles and it is expressed as,

$$\Delta\omega = \omega_{[n]} - \omega_{[n-1]} \quad \text{A.9}$$

From (A.2), (A.3), and (A.9), frequency deviation is expressed as,

$$\frac{\Delta\omega}{\omega_r} \approx \frac{1}{2q} \cdot \frac{\Delta Q_{I,1} + Q^0{}_{I,1} + \sum_{n=2}^{N} Q_{I,n}}{\Delta P_{I,1} + P^0{}_{I,1} + \sum_{n=2}^{N} P_{I,n}} \quad \text{A.10}$$

or

$$\frac{\Delta\omega}{\omega_r} \approx \frac{1}{2q} \cdot \frac{\Delta Q_{I,1} + \Delta Q + Q_{LC}}{\Delta P_{I,1} + \Delta P + P_R} \quad \text{A.11}$$

Following assumptions of the worst case islanding condition, real and reactive power mismatches are zero ($\Delta P \approx 0$ and $\Delta Q \approx 0$) and load reactive power is also zero ($Q_{LC} = 0$). Thus, frequency deviation $\Delta\omega$ in (A.11) can be further simplified as,

$$\frac{\Delta\omega}{\omega_r} \approx \frac{1}{2q} \cdot \frac{\Delta Q_{I,1}}{\Delta P_{I,1} + P_R} \quad \text{A.12}$$

A capacity ratio k ($k = P^0{}_{I,1}/P_R$) is introduced in (A.12) and it is expressed as,

$$\frac{\Delta\omega}{\omega_r} \approx \frac{1}{2q} \cdot \frac{\frac{\Delta Q_{I,1}}{P^0{}_{I,1}}}{\frac{\Delta P_{I,1}}{P^0{}_{I,1}} + \frac{1}{k}} \quad \text{A.13}$$

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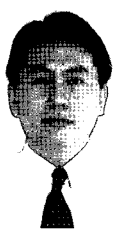

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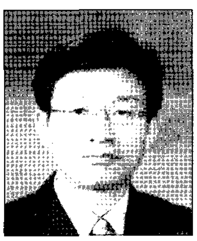

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