# A Correlation Factor Based Islanding Detection Method for Distributed Synchronous Generators

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*Abstract:* - This paper proposes a new correlation factor based islanding detection method for use of grid-connected distributed synchronous generator. The proposed correlation factor method is based on voltage fluctuation injection, which can be obtained through regulating the field current of the distributed synchronous generator periodically. The correlation factor between the periodic regulating signal and the perturbed voltage is then used as an islanding detection index. When distributed synchronous generator is grid-interconnected, the correlation factor is lower than a threshold value. In contrast, as an islanding occurs, the correlation factor would become much higher than the threshold value. In this paper, experiments are conducted to illustrate the principles of the proposed technique. The test results show that the new proposed method is reliable, economical, and easy for implementation for islanding detection of distributed synchronous generator.

*Key-Words:* - Islanding detection, Distributed synchronous generator, Voltage fluctuation injection, Periodic field current regulation, Correlation factor

## 1 Introduction

Rising crude oil prices and worldwide awareness of environmental issues are leading to the exploitation of distributed generation system. Distributed generation system is defined as the generation system of power inside the distribution system. Distributed generation system is driven by prime movers such as a wind turbine, water turbine, micro-turbine, etc. to generate electricity. Due to the technological innovations related to the energy conversion in the last decade, it is now possible to have competitive electricity generation with distributed generation units.

Many papers have been presented in literature regarding the sizing, placement, reliability, and expansion planning of distributed generation system [1-4]. The main merits of distributed generation system can be listed as follows: reduction of power loss, voltage profile improvement, power quality improvement, possibility to exploit combined heat and power generation, simple structure, high efficiency, and minimal environmental impact. Since distributed generation system is inside the distribution system, it changes the characteristics of the distribution system, causing an impact in the voltage regulation and protection scheme [5-8].

As the interest in distributed generation system grows, the urge for reliable protection schemes used in distributed generation system also increases. An essential requirement of the grid-interconnected distributed generation system is the capability of islanding detection [9]. Islanding occurs when a part of the distribution system is electrically isolated from the main source of supply, yet continues to be energized by distributed generation system. The islanding operation of distributed generation system may cause potential hazards to line-maintenance personnel, and risk the distributed generation system in being damaged by out-of phase reconnection to the grid. The majority of utilities require that distributed generation system should be disconnected from the grid as soon as the islanding occurs. IEEE standard 1547 stipulates a maximum delay of 2 seconds for detection of an islanding [10].

The islanding detection methods can be generally categorized into two groups, passive methods and active methods. Passive methods detect the islanding operation of distributed generation system by monitoring selected power system parameters, such as voltage magnitude, the change rate of frequency, phase displacement, and power output. Active methods detect the islanding by directly interacting with the system under consideration.

The passive islanding detection methods include the change of voltage magnitude relay [11], the rate of change of frequency relay [12], the vector surge relay [13], the voltage unbalance and total harmonic distortion of current relay [14], the change of output power relay [15], the ratio of the frequency change to the output power change relay [16], the rate of change of voltage and power factors relay [17], and the logical rule-based detection technique [18].

The principles of these passive islanding detection methods were developed based on the fact that an islanding will cause variations in system parameters. However, when the amount of power mismatch between the distributed generation system and local load is not significant enough during islanding, the methods mentioned above may fail to signal the abnormality. Besides, another drawback to the passive methods is that they cannot effectively differentiate between the islanding and other non-islanding transients, like voltage flicker or sag.

The three main active islanding detection methods are the reactive error export detection method, the positive feedback for power loop method, and the voltage fluctuation correlated method.

The reactive error export detection method controls the excitation current of distributed generation system so that it generates a known value of reactive current, which cannot be supported unless the generator is connected to the grid [19].

The positive feedback for power loop method will result in an unstable frequency or voltage, once the distributed generation system is islanded. Eventually, the unstable frequency or voltage will trip the frequency or voltage relay to protect islanding [20]. The small-scale distributed generation system has simple excitation, perhaps using permanent magnets. Hence, islanding of small-scale distributed generation system cannot be detected effectively by controlling the reactive power export, as in the reactive error export detection method or the positive feedback for power loop method.

The voltage fluctuation correlated method using power transistor switching high-impedance load periodically near the voltage zero crossing point, it measures the voltage fluctuation through the utility-interconnected point, enabling evaluation of system source impedance and detection of islanding. It provides a very effective means of detection, with the disadvantage of introducing a small voltage perturbation at the zero crossing point [21].

The active islanding detection methods are more effective and robust than the passive ones, but most existing active schemes have the disadvantages of high cost, complex structure, uncommon use for all kinds of generator, and degradation of power quality to a certain extent.

To overcome the disadvantages of the existing islanding detection methods, the aim of this paper is at proposing a new correlation factor based islanding detection (CFBID) method for small-scale, typically less than 1 kW, grid-connected distributed synchronous generator (DSG). To verify the proposed CFBID method for the islanding detection, a series of experiments have been employed in this paper for 4 different loads with lagging to leading power factors as specified in IEEE Standard 1547. From the test results, the proposed CFBID method has the advantages of effective, economical, and has high power quality.

## 2 Basic Principle of the Proposed Method

In the proposed CFBID method a periodic voltage fluctuation is injected on to the utility-connected point by regulating the field current of the DSG periodically, then calculates the correlation factor between the periodic regulating signal and the perturbed terminal voltage. Through the proposed method, an islanding detection index can be evaluated that serves as a useful reference to activate the protective relays.

The proposed islanding detection method is based on the feature that the variation at the terminal voltage of DSG has a strong correlation with its voltage perturbation source when DSG is operating in islanding state. On the contrary, the variation at the terminal voltage of DSG has a weak correlation with its voltage perturbation source when DSG is operating in parallel with the grid. Therefore, measuring the correlation index between variation at terminal voltage and its voltage perturbation source would show whether the DSG is operating in parallel with the grid or functioning independently of the grid. In the proposed islanding detection applications, a periodic regulating signal for the field current of the DSG is used, so that variation of load voltage is restricted to the level, which would not influence the supply.

The equivalent circuit of a DSG parallel with the grid in normal operation state is shown in Fig. 1. In Fig.1, where $E_u$ and $E_g$ are the open circuit voltage of utility and DSG; $\Delta E_g$ is the voltage fluctuation of DSG due to the periodic field current regulating, $Z_u$ is the source impedance of the utility grid; $Z_g$ is the synchronous impedance of the DSG; $Z_L$ is the local load impedance. $S_1$ is the tie-switch between the DSG and the utility grid.

As shown in Fig. 1, the tie-switch $S_1$ is turned on. The local load is energized by both utility grid and DSG. The terminal voltage of utility-connected point when DSG is connected to the grid can be expressed as

$$V_{L1} = \left(\frac{Z_g E_u}{Z_u + Z_g} + \frac{Z_u (E_g + \Delta E_g)}{Z_u + Z_g}\right) \times \frac{Z_L}{Z_L + \dfrac{Z_u Z_g}{Z_u + Z_g}} \tag{1}$$

The sensitivity of terminal voltage $V_{L1}$ to the voltage fluctuation $\Delta E_g$ can be obtained from following equation

$$\frac{\partial V_{L1}}{\partial(\Delta E_g)} = \frac{Z_u}{Z_u + Z_g} \times \frac{Z_L}{Z_L + \dfrac{Z_u Z_g}{Z_u + Z_g}} \tag{2}$$

Since $Z_g$ is significantly greater than $Z_u$ for distribution system, even for the long radial system or the weak grid system [21], so $\dfrac{Z_u Z_g}{Z_u + Z_g}$ term in (2) can be simplified as $Z_u$, Equation (2) will then be approximately calculated by

$$\frac{\partial V_{L1}}{\partial(\Delta E_g)} \cong \frac{Z_u}{Z_u + Z_g} \times \frac{Z_L}{Z_L + Z_u} \tag{3}$$

Since $Z_L$ is significantly greater than $Z_u$, so $\dfrac{Z_L}{Z_L + Z_u}$ term in (3) can be simplified as 1, Equation (3) will further be approximately expressed as

$$\frac{\partial V_{L1}}{\partial(\Delta E_g)} \cong \frac{Z_u}{Z_u + Z_g} \tag{4}$$

The equivalent circuit of a DSG subject to islanding operation is shown in Fig. 2. As shown in Fig. 2, the tie-switch $S_1$ is turned off. The local load is only energized by DSG. The terminal voltage of utility-connected point when islanding operating is given as follow

$$V_{L2} = \frac{Z_L}{Z_g + Z_L} \times (E_g + \Delta E_g) \tag{5}$$

The sensitivity of $V_{L2}$ to $\Delta E_g$ can be obtained from the following expression

$$\frac{\partial V_{L2}}{\partial(\Delta E_g)} = \frac{Z_L}{Z_g + Z_L} \tag{6}$$

Because $Z_g$ is significantly greater than $Z_u$, the sensitivity of $V_{L1}$ to $\Delta E_g$ is approximately to be zero. Compare with equation (4) and (6), the sensitivity of $V_{L2}$ to $\Delta E_g$ is significantly greater than the sensitivity of $V_{L1}$ to $\Delta E_g$. Variation at the terminal voltage due to the regulating the field current of the DSG periodically during islanding operation is thus larger than that in normal operation.

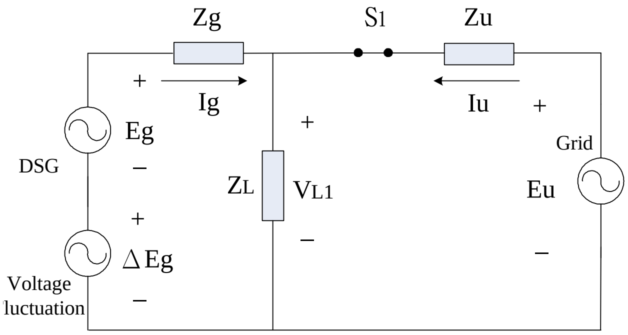


Fig. 1 Equivalent circuit of a DSG parallel with the utility grid

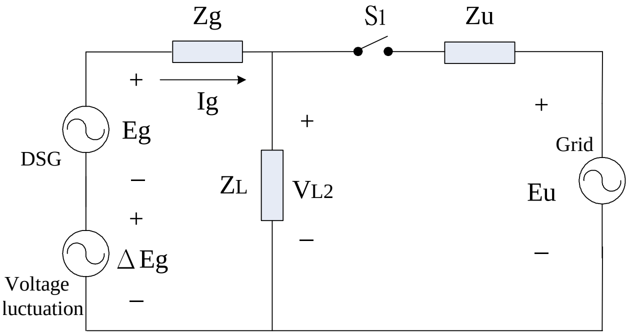


Fig. 2 Equivalent circuit of a DSG during islanding operation

A DC-DC step-down buck converter must then be used to regulate the field current of DSG with a limited variation periodically, so that the voltage fluctuation of DSG is restricted to a level, which will not disrupt the main power system. Measuring the periodic perturbation of terminal voltage due to the voltage fluctuation of DSG, allows the source impedance to be calculated. Periodically regulating the field current of DSG permits a continuous assessment of the terminal voltage and thus indirectly the source impedance.

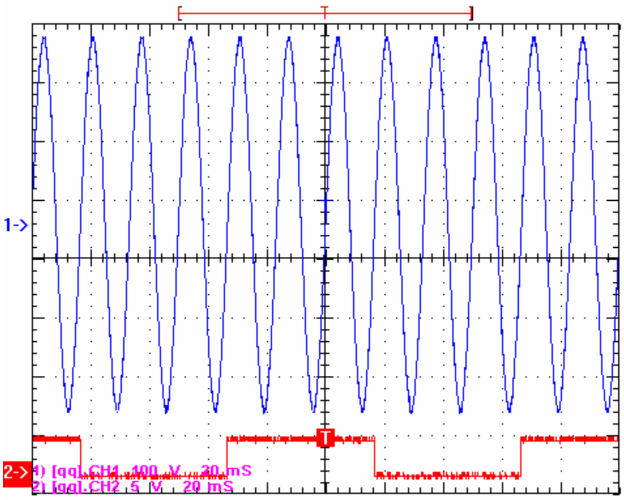
The experimental system was performed, and the results are shown in Figs. 3 to 4. The DSG employed in the tests consisted of a grid-interconnected, three-phase, 220V, 300W synchronous generator and a 100V, 50W, DC-DC step-down buck converter. As an example of the typical test for the DSG in normal operation, Fig. 3 exhibits that the variation at the terminal voltage due to the regulating of field current is very small. The frequency in the terminal voltage is 60Hz, and the frequency of the field current regulating signal is 10Hz. Waveform of terminal voltage and regulating signal during normal operation are shown in Fig. 3.

As an example of the typical test for the DSG in islanding operation, Fig. 4 exhibits that the variation at the terminal voltage due to the regulating of field current in islanding operation is larger than that in normal operation. In Figs. 3 and 4, Channel 1 denotes the waveform of the terminal voltage (100V/div), Channel 2 indicates the waveform of the regulating signal of the field current of DSG (5V/div), and the time-base is 20ms/div.

Measuring the periodical perturbation of terminal voltage at the grid-interconnected point, due to periodically regulating the field current of DSG, allows one to estimate indirectly the DSG operating state. When the variation at the terminal voltage changed, the islanding operation can be easily detected accordingly.

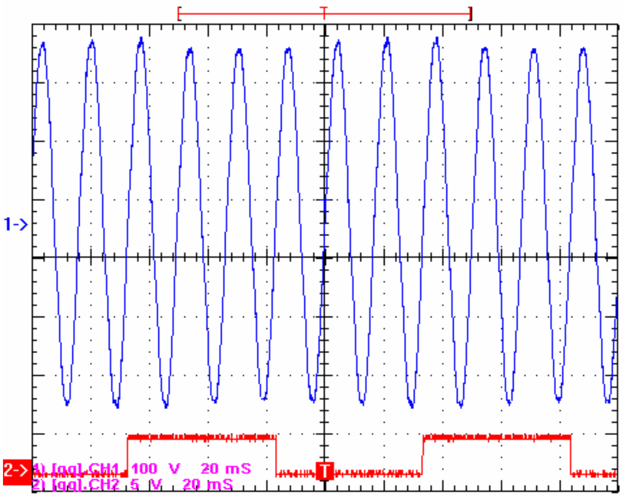
However, variations in the terminal voltage may result from some load switching, other than the periodically regulating the field current of DSG. Consequently, to avoid false alarms, the measured variation of terminal voltage should be closely related with the given DSG field current regulating signal as in the islanding operation. Nevertheless, in the case of some load changes occurring coincidentally with the intentional field current regulating, the measured voltage fluctuation may not represent the supply impedance change. Distinction between intentional and coincidental load changes should be made by observing a number of more switching instances and terminal voltage changes [21]. To effectively distinguish variations of the terminal voltage due to the periodically regulating the field current of DSG from the others should thus be based on correlation of the measured terminal voltage changes with the given load switching.

When the source impedance has increased with a larger perturbation of terminal voltage measured due to the given field current regulating, the islanding operation can be easily detected. Variations in the terminal voltage may not be due to the deliberately regulated field voltage, and so the voltage change needs to be correlated with the field current regulating. Also, other load changes may occur coincidentally, giving a terminal voltage fluctuation that may not be representative of the field current regulating. The distinction between deliberately field current regulating and coincidental load changes may be made, by considering a number of regulating instances and terminal voltage changes. However, to distinguish the variations of the voltage due to the regulating of the field current of DSG from the others, needed is the correlation of the measured terminal voltage changes with the given field current regulation signal.



(1)CH1:100V/div (2)CH2:5V/div Time:20ms/div

Fig. 3 Waveform of terminal voltage and regulating signal during normal operation



(1)CH1:100V/div (2)CH2:5V/div Time:20ms/div

Fig. 4 Waveform of terminal voltage and regulating signal during islanding operation

## 3 The Proposed Detection System

The hardware, which formed the CFBID system, consisted of two sections as illustrated in Fig. 5. The pulse width modulation (PWM) based DC-DC step-down buck converter formed one section and performed regulating the field current of DSG, while the second section consisted of a digital signal processor (TI TMS320LF2407). With a voltage detecting interface to measure the magnitude of terminal voltage, digital signal processor calculates the correlation factor between the periodic regulating signal and the perturbed terminal voltage and decides whether the trip conditions were met.

At the zero crossing point of terminal voltage, the PWM based DC-DC step-down buck converter regulates high/low status every three cycles. The terminal voltage fluctuation due to the periodical field current regulating during islanding operating is significantly greater than that during the normal operating.

As mentioned before, the PWM based DC-DC step-down buck converter regulates up/down status every three cycles. The regulating status signal function $S(j)$ has a period of six cycles. $S(j)$ has only two values, -1 for regulating down status and +1 for regulating up status, as shown in Fig. 5. The differential $S(j)$ of $j$th cycle is described as follow

$$\Delta S(j) = S(j) - S(j-3) \tag{7}$$

The time series of differential terminal voltage with time lag of 3 cycles, as described in (8)

$$\Delta V_L(j) = V_L(j) - V_L(j-3) \tag{8}$$

where the $V_L(j)$ is the terminal voltage of $j$th cycle.

Since the average terminal voltage progressively increases during the regulating up period and decreases progressively during the regulating down period, a proportional function $P(j)$ is used to express this feature. $P(j)$ is experimentally set to be 1 for the first cycle after regulating, 2 for the second cycle, and 3 for the third cycle for enhancement of the voltage progressive varying trends after regulating up and down the field current. The correlation factor between $\Delta S(j)$ and $\Delta V_L(j)$ is expressed as follow

$$F_k = \frac{1}{N} \sum_{k=j-N}^{j} \Delta V_L(k) \times \Delta S(k) \times P(k) \tag{9}$$

where $F_k$ is the proposed correlation factor, as an islanding detection index, $N$ is the number of cycles of the observing window, and $N$ is set as 6 in this paper.

As described previously, in normal operation the correlation between $\Delta V_L(j)$ and $\Delta S(j)$ is weak and $F_k$ is much lower than a threshold value. In contrast, as an islanding occurs, $\Delta V_L(j)$ and $\Delta S(j)$ have a strong correlation and $F_k$ is significantly greater than that in normal operation [22,23]. Through the proposed scheme, the correlation factor can be used as an islanding detection index and serves as a useful reference to activate the islanding protective relays.

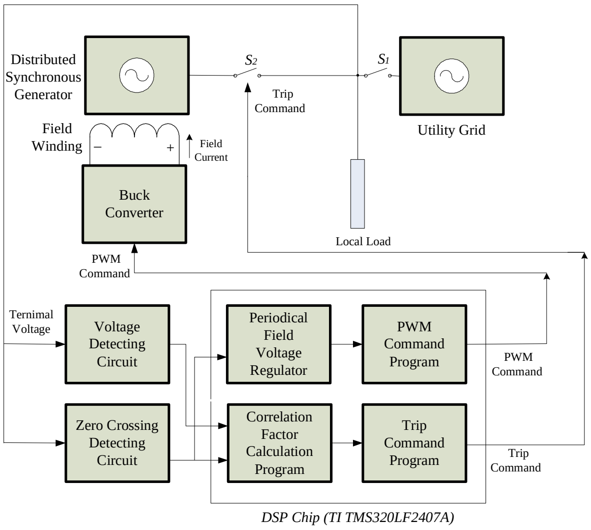


Fig.5 System configuration of the correlation factor based islanding detector

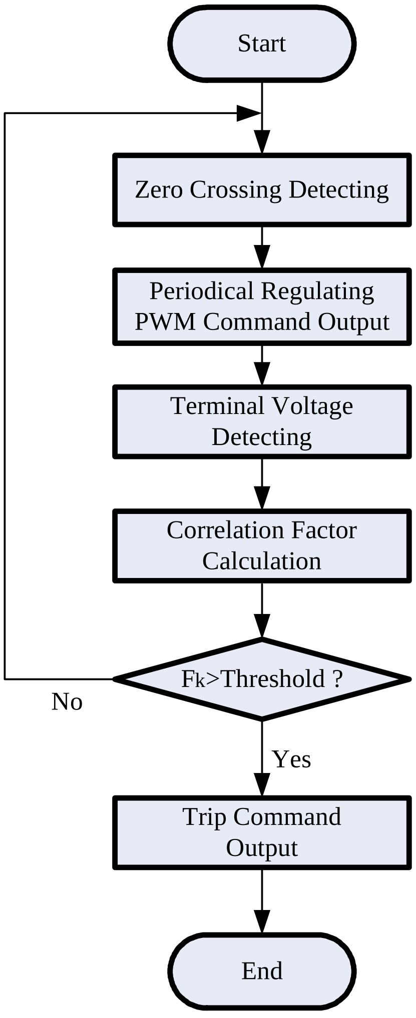


Fig. 6 Procedure of the CFBID method

Fig. 6 depicts the procedure of the CFBID method. It consists of zero crossing detection, periodical regulating PWM command generation, terminal voltage detection, correlation factor calculation, and decision process. The digital signal processor measures the value of terminal voltage over 6 cycles, so that it avoids the impacts of various load variations and real power or reactive power disturbances. As shown in Fig. 6, a threshold for the islanding detection correlation factor is defined; the threshold is set to be 30 in this paper.

Computer simulations were performed, and the simulation results of the variation of the correlation factor $F_k$ before and after the islanding operation are shown in Fig. 7. As shown in Fig.7, if the islanding fault is occurring at the 6th cycle, then the correlation factor $F_k$ increases during the next 6 cycles. At the 12th cycle the correlation factor $F_k$ larger than the threshold *Top* $F_k$, and the islanding has been detected.

## 4 Experimental Results

To verify the proposed method, experiments were conducted to demonstrate its effectiveness of the islanding detection approach. The experimental tests were carried out on DSG. The procedures of the tests are to verify that the DSG systems cease to energize the utility grid as specified in IEEE Standard 1547 when an unintentional island condition is present.

The generation system employed in the islanding tests for DSG consisted of a grid-interconnected, three-phase, 220V, 300W synchronous generator driven by a DC motor with 4 types of loads, including (a) maximum real load at unity power factor, (b) maximum real load at rated power factor lagging, (c) maximum real load at rated power factor leading, and (d) minimum load at unity power factor. The test circuit, specified in IEEE Standard 1547, is configured as shown in Fig. 8. The DSG is started, synchronized to the utility grid, and then the tie-switch $S_2$ is closed to interconnect the DSG to the grid. Open switch $S_1$ and record the time between the opening of switch $S_1$ and when the DSG ceases to energize the load. Repeat test to 4 types of loads for a total of 5 times. The test is successful when the DSG ceases to energize the test load within the timing requirements of IEEE Standard 1547 after switch $S_1$ is opened. The experimental set-up is depicted in Fig. 9.

The effectiveness of the correlation factor method for DSG has been validated in the experiments. The test results for 4 types of loads are shown in Table 1. The testing results show that the correlation factor, used as an index of islanding detection, can detect

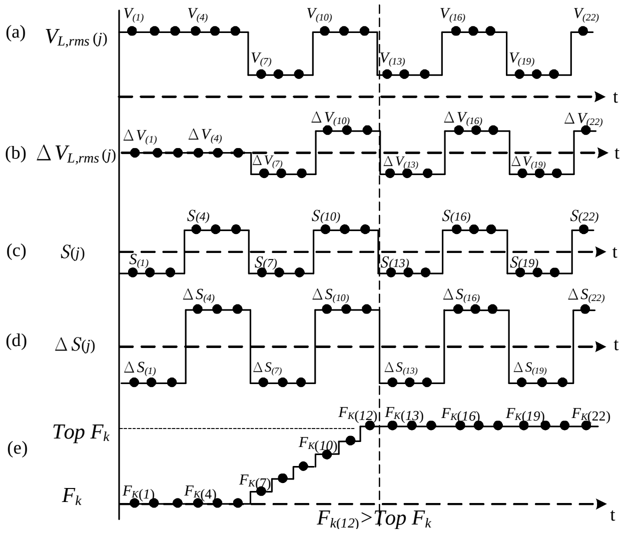


Fig.7 The simulation of the variation of $F_k$ before and after the islanding operation

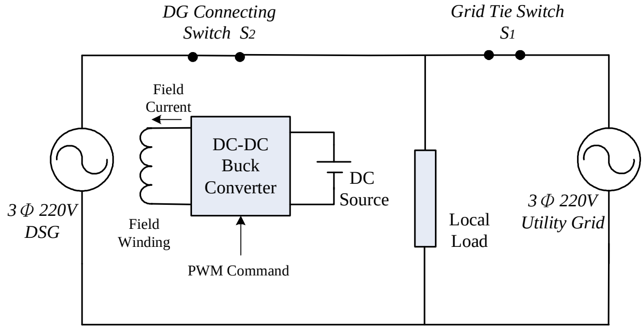


Fig.8 The islanding test configuration for synchronous generator

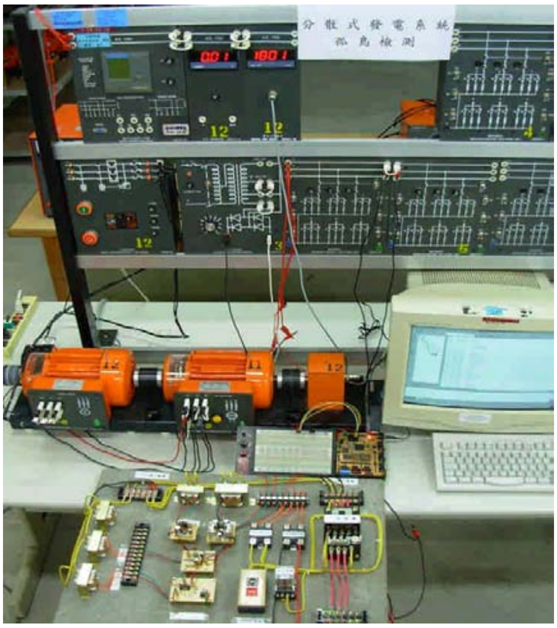


Fig. 9 View of the experimental set-up

the islanding operation easily and accurately. The verification results also reveal that the proposed correlation factor method detected the islanding event with a maximum delay time of 0.224 seconds in the 20 tests for 4 types of loads. The average detection time of the 20 tests is 0.123 seconds. The detection time needed is much less than the maximal 2 seconds as specified by IEEE standard 1547.

In the typical test for the type (a) load, as shown in Fig. 10, the detection signal for islanding was issued in 0.083 seconds (totally 5 cycles for estimating the differential voltage magnitudes were needed) after the islanding operation started.

In the typical test for the type (b) load, as shown in Fig. 11, the detection signal for islanding was given in 0.158 seconds (totally 9.5 cycles needed) after the islanding operation started.

In the typical test for the type (c) load, as shown in Fig. 12, the detection signal for islanding was likewise announced successfully in 0.133 seconds (totally 8 cycles needed) after the islanding operation started.

In the typical test for the type (d) load, as shown in Fig. 13, the detection signal for islanding was likewise announced successfully in 0.0916 seconds (totally 5.5 cycles needed) after the islanding operation started.

In Figs. 10 to 13, Channel 1 denotes the waveform of grid voltage (400V/div), Channel 2 indicates the waveform of local load terminal voltage (400V/div), Channel 3 depicts the waveform of the regulating signal of the field current of DSG (5V/div), Channel 4 shows the tripping signal (5V/div), and time-base is 40ms/div.

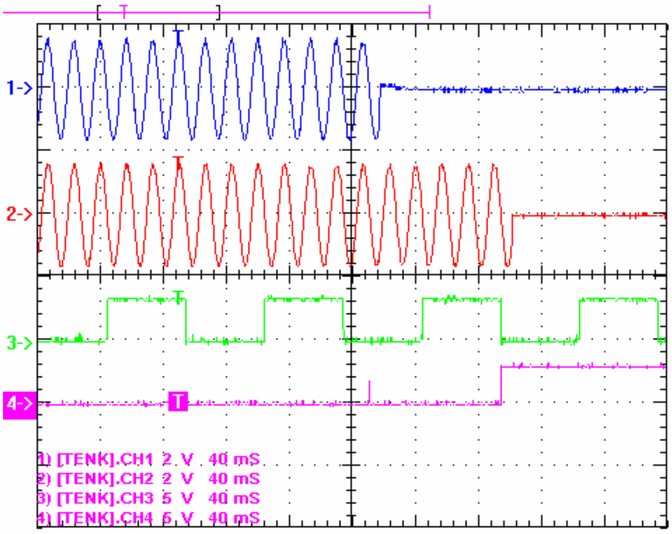
The capability of the proposed system to avoid false alarms was verified through the experiments of randomly switching the loads. The random load switching tests were taken 200 times for each type of load; results depict that no false alarm occurred out of the 800 switching tests. As an example of the typical test for the load at unity power factor, Fig. 14 exhibits that the detection system does not have false alarms due to the load switching.

In Fig. 14, Channel 1 denotes the waveform of grid voltage (400V/div), Channel 2 indicates the waveform of load current (4A/div, the transfer rate of current probe is 1A/50mV), Channel 3 depicts the waveform of the regulating signal of the field current of DSG (5V/div), Channel 4 shows the tripping signal (5V/div), and time-base is 40ms/div.

To further evaluate the impact on the power quality due to the periodical voltage fluctuation injection by using the CFBID method, three power quality indices were measured through a power quality analyzer. The three power quality indices

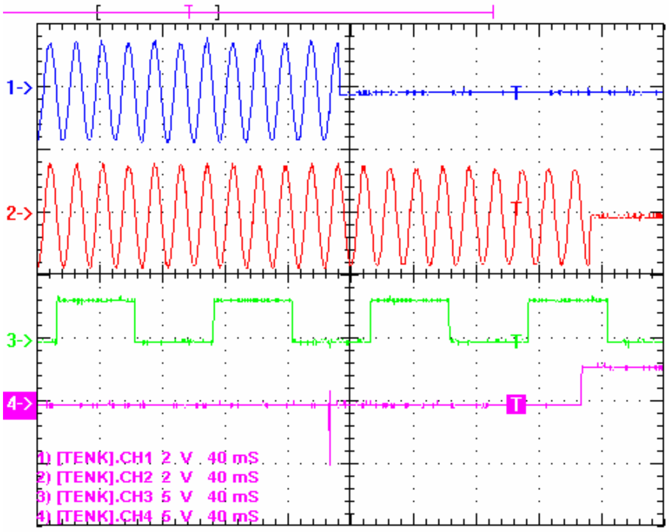
Table 1 Islanding test results for DSG

| Load Type | Average trip time (ms) | Maximum trip time (ms) | Minimum trip time (ms) | Success times |
|---|---|---|---|---|
| (a) | 81.7 | 110 | 60.8 | 5 |
| (b) | 138.8 | 216 | 76 | 5 |
| (c) | 109.1 | 166 | 58.4 | 5 |
| (d) | 163.8 | 224 | 99.2 | 5 |



CH1:400V/div,CH2:400V/div, CH3:5V/div, CH4:5V/div, Time:40ms/div

Fig.10 The results of the experiment for DSG using type (a) load



CH1:400V/div,CH2:400V/div, CH3:5V/div, CH4:5V/div, Time:40ms/div

Fig.11 The results of the experiment for DSG using type (b) load evaluated are total harmonic distortion (THD), voltage fluctuation ($P_{ST}$), and three phase unbalance. Comparison results between with and without the voltage fluctuation injection are given in Table 2. The table shows that in normal operation of DSG interconnected with the utility grids, though regulating the field current of DSG occurred at the grid-interconnected point, the terminal voltage almost was not influenced. The differences between with and without the voltage fluctuation injection as shown in Table 2 are supposed to result from errors or noise from the measurement instrument.

## 5 Conclusions

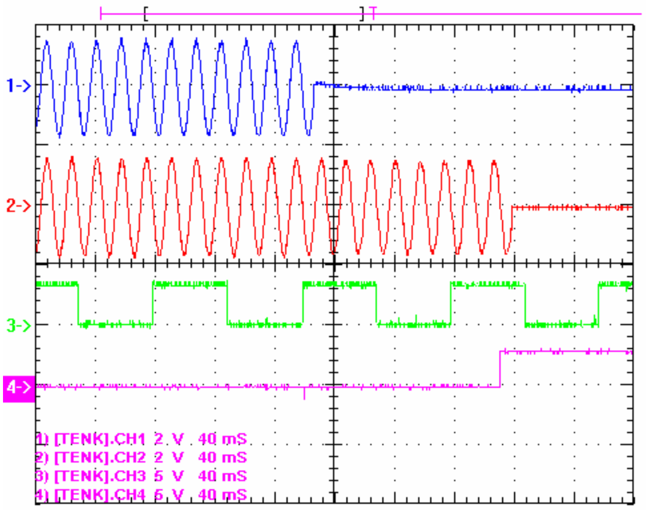
This paper has proposed a new islanding detection method, based on a correlated voltage fluctuation concept, to quickly and economically detects islanding for DSG. A voltage fluctuation was injected on to the utility-connected point by regulating the field current of DSG periodically. Observing the correlation factor of the proposed CFBID method through a digital signal processor, discrimination between islanding and other non-islanding disturbances can thus be made accurately.

To verify the effectiveness of the proposed method, results obtained from experiments are used in this paper. The experimental results show that the proposed index of the islanding detection, correlation factor, can detect the islanding operation satisfactorily for different types of loads within 0.224 seconds. The performance of the CFBID method for DSG is less dependent on load quality factor and load power level, as well as more reliable than traditional passive detection methods. Besides, the test results also reveal that the new proposed method is easier and more economical for implementation as compared to the existing active detection approaches.

The directions for future research of the islanding detection method can be described as follow: To further improve the detection performance of the proposed active islanding detection method, the passive islanding detection methods that detect the islanding operation of DSG by monitoring the selected power system parameters will be investigated and integrated in the proposed active method. Besides, for the passive islanding detection methods, there are many power system parameters to be monitored, such as voltage magnitude, the change rate of frequency, phase displacement, and power output. The using of optimization search methods, such as genetic algorithm or neural networks, for the best combination selection of the

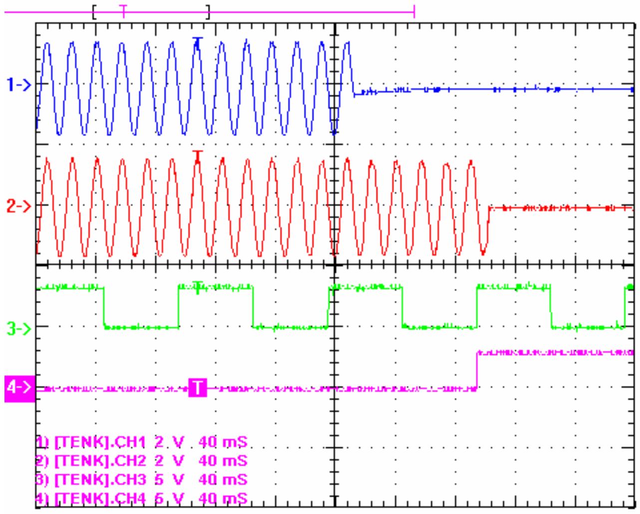
Table 2 Impact on the power quality due to voltage fluctuation injection

| Condition | Power quality index | Phase | | |
|---|---|---|---|---|
| | | A | B | C |
| With voltage fluctuation injection | THD | 0.7% | 0.8% | 0.6% |
| | PST | 0.23 | 0.23 | 0.25 |
| | 3ϕ unbalance | 0.3% | | |
| Without voltage fluctuation injection | THD | 0.6% | 0.8% | 0.6% |
| | PST | 0.22 | 0.18 | 0.3 |
| | 3ϕ unbalance | 0.3% | | |



CH1:400V/div, CH2:400V/div, CH3:5V/div, CH4:5V/div, Time:40ms/div

Fig.12 The results of the experiment for DSG using type (c) load



CH1:400V/div, CH2:400V/div, CH3:5V/div, CH4:5V/div, Time:40ms/div

Fig.13 The results of the experiment for DSG using type (d) load selected power system parameters will be investigated in the passive islanding detection methods.

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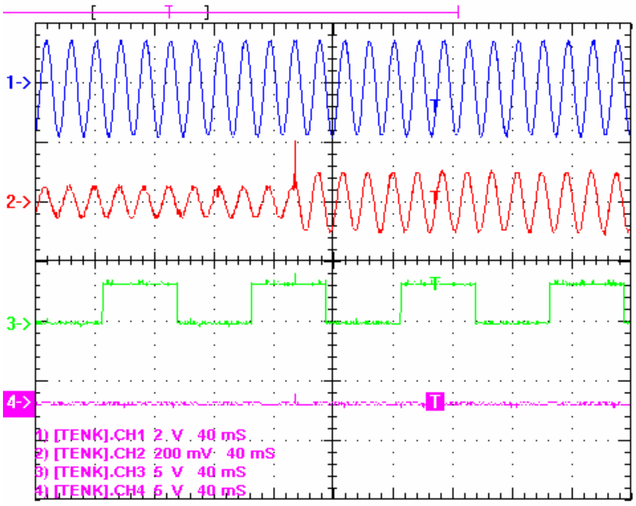

CH1:400V/div, CH2:4A/div, CH3:5V/div, CH4:5V/div, Time:40ms/div

Fig.14 The results of the experiment for randomly switching of the load

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