A Bilateral Reactive Power Injection Method for Islanding Detection of Grid-connected Converters in Distributed Generation Units

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Abstract-- **In this paper, a bilateral reactive power injection method is proposed for islanding detection of grid-connected converters in distributed generation units. The proposed method injects capacitive and inductive reactive power periodically with half of the grid frequency to perturb the frequency of point of common coupling (PCC). The magnitude of the injected reactive power is derived in order to remove the non-detection zone and the frequency of the injected reactive power is determined by considering parallel operation of the converters with no communication. In addition, the distortion of the currents by the proposed detection method is analyzed. The effectiveness of the proposed method is experimentally verified through the operation of two converters used for a 10kW battery energy storage system.**

Index Terms— **LCL filter, active damping, grid-connected converter, capacitor current feedback.**

I. INTRODUCTION

Due to the environmental concerns, distributed generation (DG) units based on renewable energy sources and battery sources are increasingly installed in recent years [1]. However, DG systems suffer from several technical difficulties and islanding detection is one of the issues. Islanding refers to the condition in which the distributed generation units continue to provide power for their local loads even though electrical grid power from the utility is no longer present. Unintentional islanding causes electrical damages to loads, poor power quality and safety hazards. Consequently, regulations such as IEEE Std. 929 and IEEE Std. 1547 specify the requirements on islanding detection.

Numerous researches have been reported for islanding detection methods and they are largely divided into three categories: 1) Communication-based methods; 2) Passive methods; 3) Active methods.

Among them, communication-based methods are relatively rarely used because the implementation is complicated and the cost for the implementation is much higher compared to the other two methods [2].

Passive methods normally monitor the system parameters such as magnitude of the voltage, frequency, phase or harmonics without any intentional operation of the grid-connected converters. The two main passive methods are to detect the over/under voltage and over/under frequency conditions. Hence, in those passive methods, there exist non-detection zones according to the loads and converter output conditions and islanding detection may fail [3].

On the other hand, active methods intentionally perturb the output power of the converter and force the islanded system to be out of normal operation range [4]. The active methods are generally known to be able to reduce or eliminate the non-detection zones and therefore they are most widely used.

Among the reported active methods, reactive power injection schemes are attractive because of the simplicity of the implementation [5-6]. The converter periodically changes its output reactive power and then the system frequency at the islanding drifts away from the normal operation region.

However, the design of the amplitude and the frequency for the injected reactive power is not described in detail. Especially, the performance of the islanding detection is severely affected when the converters simultaneously implement the same anti-islanding schemes in the parallel operation of converters [7].

In this paper, an active method based on bilateral reactive power injection is proposed. The proposed method injects capacitive and inductive reactive power periodically with a quarter grid frequency. The magnitude of the injected reactive power is derived in order to remove the non-detection zone and the frequency of the injected reactive power is determined by considering parallel operation of the converters with no communication. The effectiveness of the proposed method is experimentally verified with two converters used for a 10kW battery energy storage system.

II. SYSTEM CONFIGURATION

The system is configured as shown in Fig. 1 for the test of the islanding detection scheme. Two converters share the DC link voltage of a battery and LCL filters are inserted as the interfaces between the converters and the grid. The static transfer switch (STS) is installed to disconnect DG from the grid for the stand-alone operation. The load is basically consisted of RLC as indicated in IEEE Std. 929 or IEEE Std. 1547 for the verification of the islanding performance. Furthermore, an induction machine is also applied for the consideration of additional load condition, which will be shown in the experimental results.

The two converters individually implement the proposed islanding detection method and the anti-islanding performance is investigated. The grid is simulated by a programmable ac power supply. Specification of the system is summarized in TABLE I.

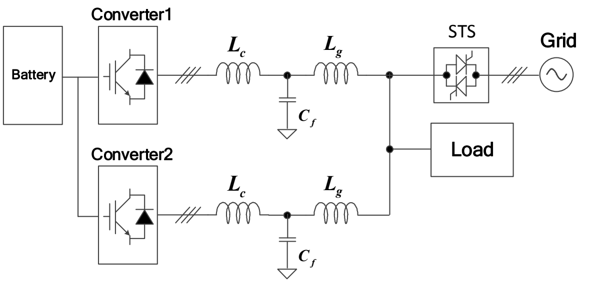


Fig. 1. System configuration.

TABLE I. SYSTEM SPECIFICATION.

Rated energy of battery	25.6[kWh]
Rated capacity of battery	62[Ah]
Rated DC link voltage	414.4[V]
Rated line to line grid voltage	220[V]
Rated grid current	37.1[A]
Grid frequency	60[Hz]

III. TEST CIRCUIT OF ISLANDING DETECTION

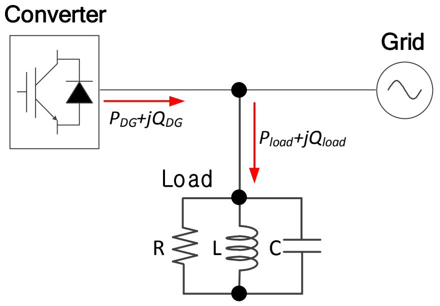


Fig. 2. Test circuit for islanding detection.

TABLE II. PARAMETERS FOR TEST CIRCUIT.

Standard	Resonant frequency (f_{LC})	Quality factor (Q_f)
IEEE 1547	f_{grid}	1±0.05
IEEE 929-2000	f_{grid}	2.5
UL 1741	f_{grid}	≤2.5

$$f_{LC}=\frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{1}$$

$$Q_f=R\sqrt{\frac{C}{L}} \tag{2}$$

The test circuit for the verification of the islanding detection method is shown in Fig. 2. TABLE II specifies the parameters of the test circuit for three typical international standards for the verification of islanding detection and the definitions for f_{LC} and Q_f are given as in (1) ~ (2). The resonant frequency of the load, f_{LC}, is set as the grid frequency, f_{grid}, in the three standards but Q_f varies according to the standard.

The load resistor in the test circuit can be designed by considering the active power of the load, P_{load}. In the three phase system, the resistor is determined by (3) with the given rated line to line grid voltage (V_{grid_rms}) and the inductor and the capacitor are calculated by equating (3) with (1) and (2) as in (4) ~ (5).

$$R=\frac{3V_{grid\_rms}^{2}}{P_{load}} \tag{3}$$

$$L=\frac{R}{2\pi f_{LC}Q_f} \tag{4}$$

$$C=\frac{Q_f}{2\pi f_{LC}R} \tag{5}$$

The magnitude (V_{ID_rms}) and the frequency (f_{ID}) of the grid at islanding are determined by the relations between the power of the distributed generation units and the loads. Under R, L, C loads as in the test circuit, the loads' power is given as (6) and (7). Then, when the supplied active and reactive power from the distributed generation units are defined as P_{DG} and Q_{DG}, the magnitude and the frequency of the grid at islanding are decided by (8) and (9).

$$P_{load}=3\frac{V_{grid\_rms}^{2}}{R} \tag{6}$$

$$Q_{load}=3V_{grid\_rms}^{2}\left(\frac{1}{2\pi f_{grid}L}-2\pi f_{grid}C\right) \tag{7}$$

$$V_{ID\_rms}=V_{grid\_rms}\sqrt{\frac{P_{DG}}{P_{load}}} \tag{8}$$

$$f_{ID}=\frac{-\frac{Q_{DG}f_{LC}}{P_{DG}Q_f}+\sqrt{\left(\frac{Q_{DG}f_{LC}}{P_{DG}Q_f}\right)^{2}+4f_{LC}^{2}}}{2} \tag{9}$$

As indicated in (8) and (9), the magnitude of the grid voltage is dependent on the active power ratio while the frequency of the grid at islanding is affected by the reactive power provided by the distributed generation units. Traditionally, reactive power variation schemes have been conducted to drift the frequency of (9), as shown in IV.

IV. CONVENTIONAL REACTIVE POWER INJECTION METHOD

In [5], a bilateral reactive power injection method was proposed with the magnitude smaller than 2.5% of the active power as shown in Fig. 3. However, as the derivation process of the magnitude for the injected reactive power is unclear and actually it is insufficient, there exists non-detection zones [4].

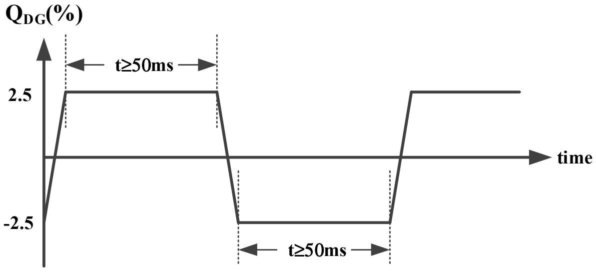


Fig. 3. 2.5% reactive power injection method by [5].

In [6], an improved bilateral reactive power injection method was reported by increasing the reactive power reference to 5% of the active power. By considering the islanding detection time limit of 2s, the reactive power was injected intermittently as shown in Fig. 4. However, it has been found out that even 5% is also insufficient for the islanding detection and in addition it could fail to detect when the injection of the reactive power of the converters in parallel operation is not synchronized.

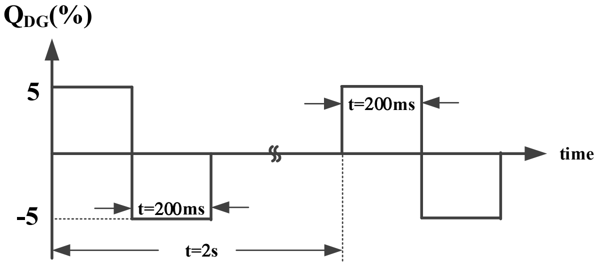


Fig. 4. Intermittent 5% reactive power injection method by [6].

The critical point in the implementation of the islanding detection methods lies in whether it would properly work in the parallel operations of the converters without any communication tool. Even though the detection method succeeds for the single distributed generation unit, the possibility of the detection would decrease for the multiple converters [7]. The worst cases in the operation of two distributed generation units for the methods in [5] and [6] are shown in Fig. 5 and Fig. 6, respectively. As the reactive power with the inverse sign is injected, it is equivalent to be zero reactive power injection and thus there exist non-detection zones as in the passive detection methods.

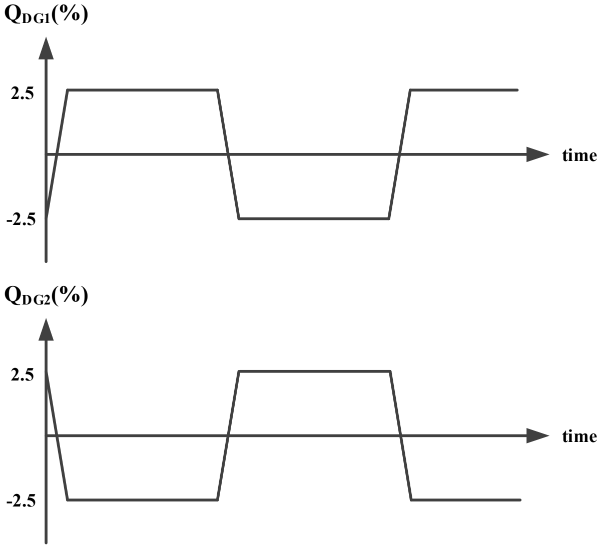


Fig. 5. Improperly synchronized 2.5% reactive power injection method by [5].

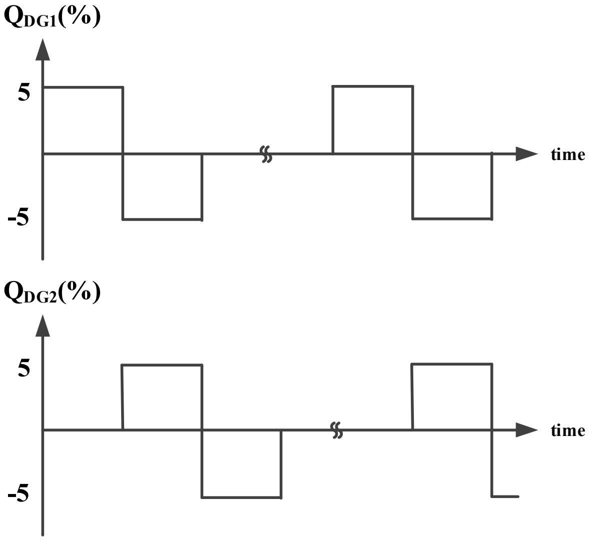
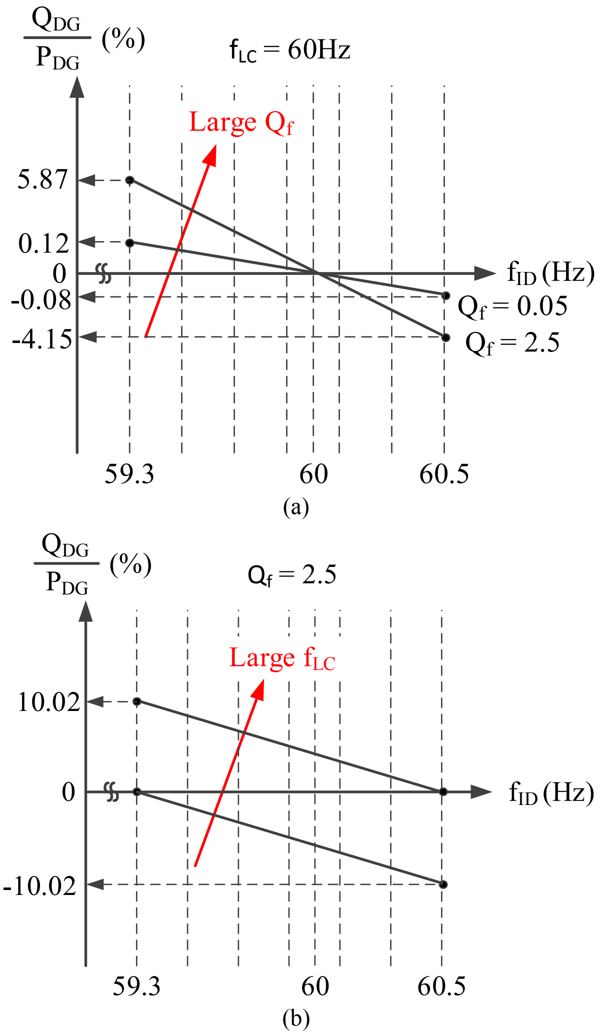


Fig. 6. Improperly synchronized 5% reactive power injection method by [6].

V. PROPOSED DETECTION METHOD

In this paper, an active detection method based on the bilateral reactive power injection as the conventional methods is proposed. However, in the proposed method, the magnitude of the injected reactive power is accurately derived by considering variations of the parameters in the test circuit and the frequency of the injection is determined for the proper operation of the multiple converters.

For the derivation of the magnitude of the reactive power to be injected, the relationship between the power of distributed generation unit and the system frequency at islanding, f_{ID}, which is given by (9), is depicted in Fig. 7 according to the variation of Q_f and f_{LC}. It is seen that Q_f affects the slope of the curve while f_{LC} makes offset effects on the curve.



(a)

(b)

Fig. 7. Relationship between power of distributed generation unit and f_{ID} according to (a) Q_f and (b) f_{LC}.

If under frequency or over frequency is used for the islanding detection, the reactive power to be injected varies depending on the load condition. Therefore, when the information on the load power is unknown at islanding, constant reactive power injection fails in the detection and there exists the non-detection zones. Consequently, a bilateral reactive power is injected in this paper.

Based on the derivation in Fig. 7, the magnitude of the reactive power to be injected can be determined. For f_{LC} of 60Hz as in Fig. 7(a), as Q_f of the load is increased, more reactive power is required to cause over frequency and under frequency in the case of islanding. In addition, it is noticed that the required reactive power is asymmetric. This asymmetry is affected by f_{LC} as shown in Fig. 7(b). To consider the symmetric injection for the reactive power, the case for f_{LC} of 59.897Hz is shown in Fig. 8. Then, if the maximum Q_f of the load is limited by 2.5 as indicated in IEEE Std. 1547, the reactive power to be injected to cause over/under frequency is calculated as 5.01%. Therefore if capacitive and inductive power with magnitude larger than 5.01% is injected periodically, over frequency or under frequency always occurs regardless of the load parameters.

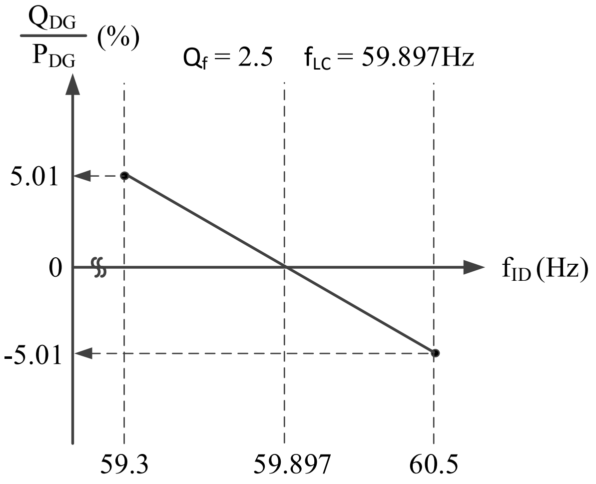


Fig. 8. Load condition for symmetric reactive power injection.

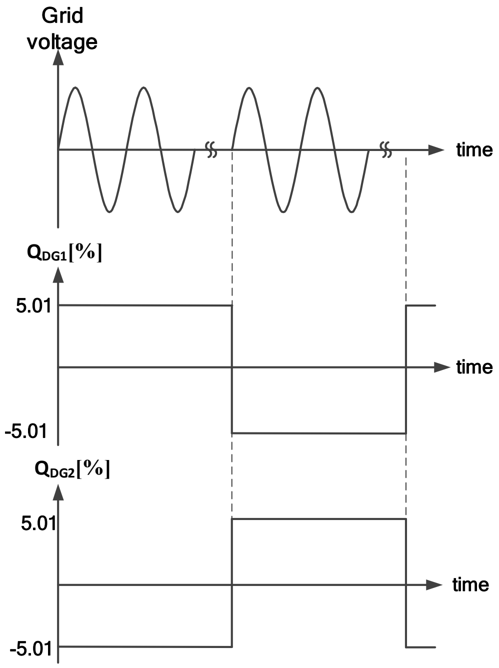


Fig. 9. Reactive power injection with period longer than fundamental grid period.

Then the period of the bilateral reactive power injection needs to be determined. When multiple converters are operated without any communication aid, the injected reactive power could be different from the intended magnitude in total as shown in Fig. 5 and Fig. 6 and hence no under frequency or over frequency occurs. Therefore, the grid voltage can be used as a common source for the synchronization of the multiple converters. However, when the period of the injection is longer than the fundamental grid period, the injected reactive power from each converter would possibly be cancelled as shown in Fig. 9, which leads to the fail in the islanding detection. In the end, it is concluded that the injection frequency must be shorter than the fundamental grid period.

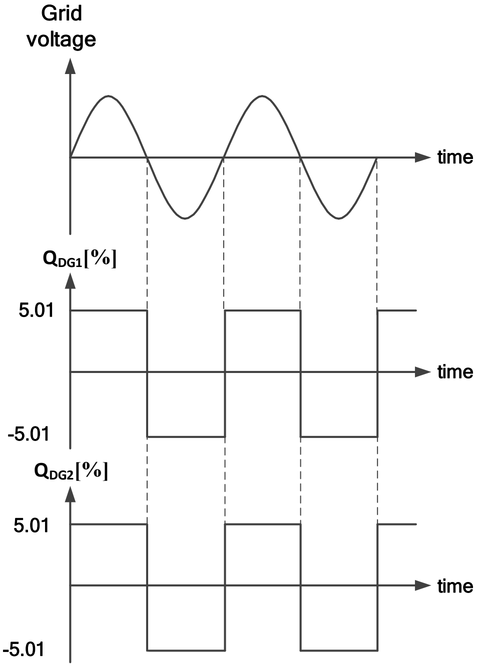


Fig. 10. Reactive power injection with grid frequency.

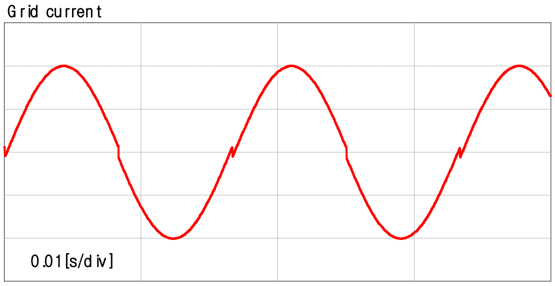


Fig. 11. Grid current waveform for reactive power injection with grid frequency.

Then, when the bilateral reactive power is injected with the grid frequency as shown in Fig. 10, the multiple converters are always in the synchronization and thus no reactive power would be cancelled. However, due to the reactive power injection with the grid frequency, the waveform of the current flowing into the grid in normal grid conditions is as of Fig. 11. Especially, even number harmonics are included in the grid current as shown in Fig. 12, which are more strictly limited by the grid standard such as IEEE 519-1992. In conclusion, the reactive power injection with the grid frequency is impractical to be implemented.

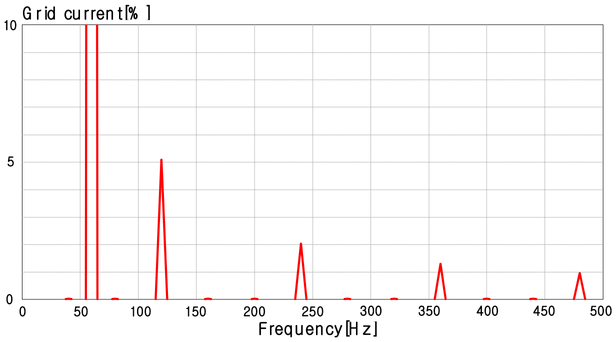


Fig. 12. Grid current waveform for reactive power injection with grid frequency.

Another candidate for the frequency of the reactive power injection is a half of the grid frequency while the synchronization is still valid. In this case, the reactive power is injected for the two converters as in Fig. 13 and the waveform of the current flowing into the grid in normal conditions is given as in Fig. 14. The harmonics spectrum is shown in Fig. 15. As expected, the even harmonics are replaced by odd harmonics and it is under the limit of the grid regulation such as IEEE 519-1992.

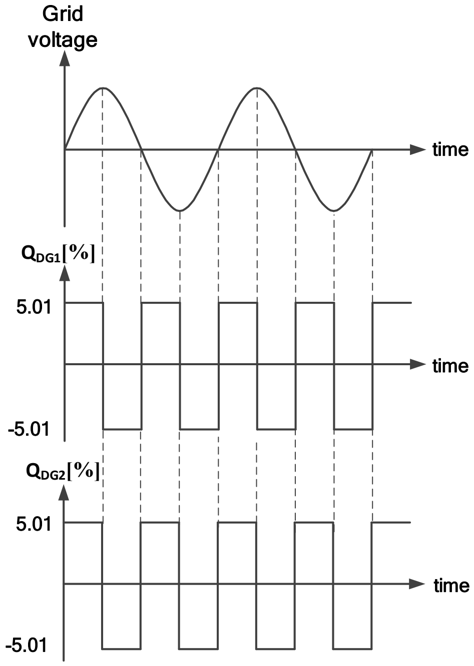


Fig. 13. Reactive power injection with a half grid frequency.

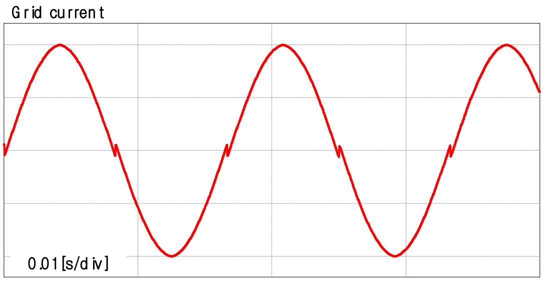


Fig. 14. Grid current waveform for reactive power injection with a half grid frequency.

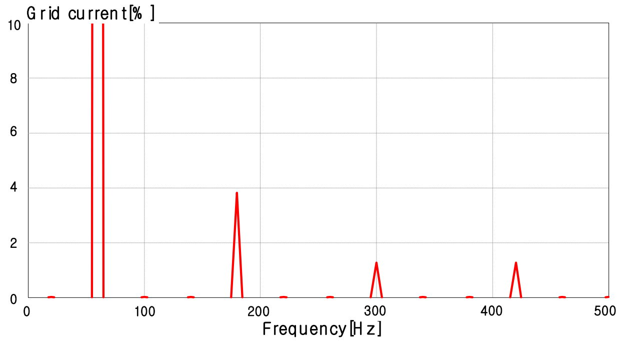


Fig. 15. Grid current waveform for reactive power injection with a half grid frequency.

VI. Experimental Results

To verify the proposed method, experiments are carried out with a battery energy storage system connected to two converters as shown in Fig. 1. The parameters for the load are given in Table III. To identify the load characteristics, the system frequency without connection to the grid is measured by varying the output reactive power. The result is shown in Fig. 16 and it is expected that the 5.01% of bilateral reactive power injection would produce under frequency (59.3Hz) or over frequency (60.5Hz) at islanding. By considering margin for implementation, reactive power with 6% of the active power is injected.

Table III. Load Parameters

Load resistor (R)	9.65[Ω]
Load inductor (L)	10.3[mH]
Load capacitor (C)	685[μF]
f_{LC}	60[Hz]
Q_f	2.5

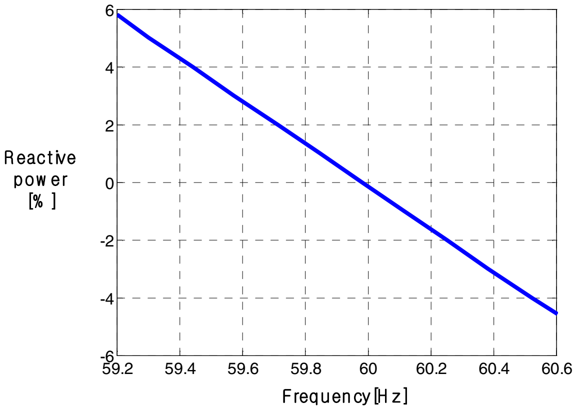


Fig. 16. Load characteristics between reactive power and frequency at islanding.

To verify the effectiveness of the proposed islanding detection method, experiments have been carried out in various load conditions. In Fig. 17, the islanding detection performance of a single converter system with no reactive power injection is shown. Even though the islanding occurs, the voltage magnitude and the frequency maintain as before because the supplied power of 5kW is in balance with the load. Therefore the islanding detection has not been achieved.

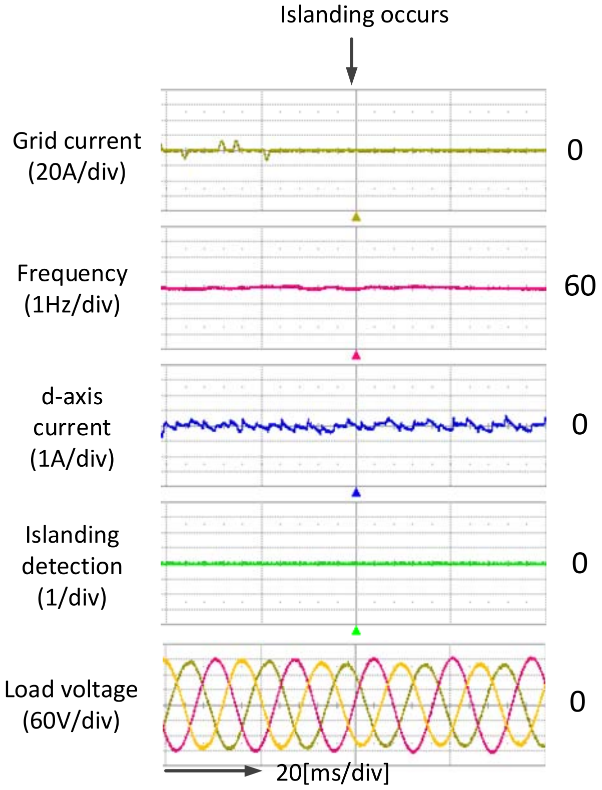


Fig. 17. Performance of islanding detection with no reactive power injection.

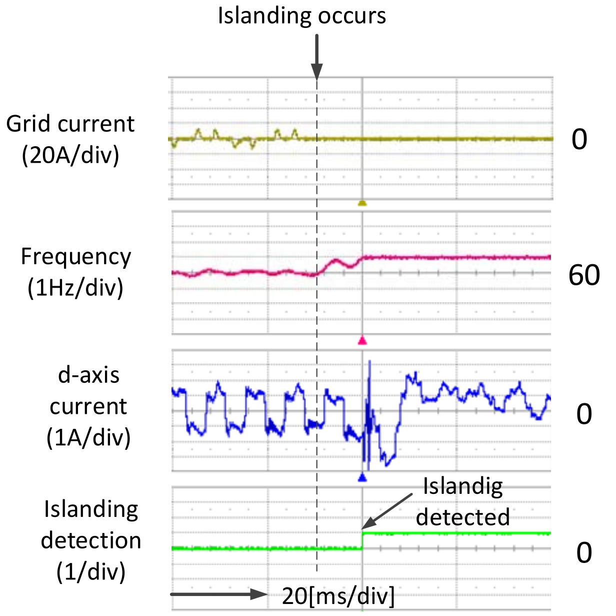


Fig. 18. Performance of the proposed islanding detection method in the same condition with in Fig. 17.

In Fig. 18, in the same load condition as in Fig. 17, the performance of the proposed islanding detection method is depicted. Due to the injected bilateral reactive power, the frequency drifts to the over frequency limit and then the detection has been achieved. The waveform of the converter current generated by the proposed method, the converter current is measured as in Fig. 19.

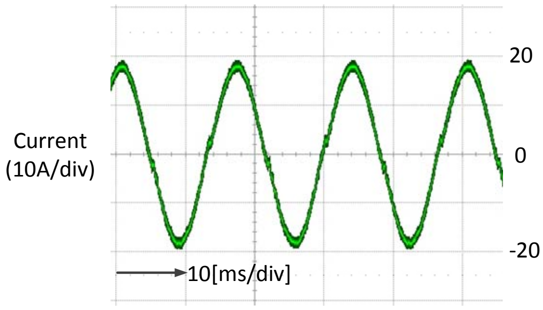


Fig. 19. Injected converter current of the proposed islanding detection method.

The proposed method has been verified in the parallel operation of the two converters. In Fig. 20, the two converters provide 10kW while the load consumes 5kW and in Fig. 21 the two converters provide 5kW in total while the load consumes 10kW. From the results in the figures, the effectiveness of the proposed islanding detection method for the parallel operation is confirmed.

The proposed islanding detection method has been verified with a load of an induction motor, which is widely used in commercial building and industry. In Fig. 22, the load motor is shown and the result for the single motor load is depicted in Fig. 23.

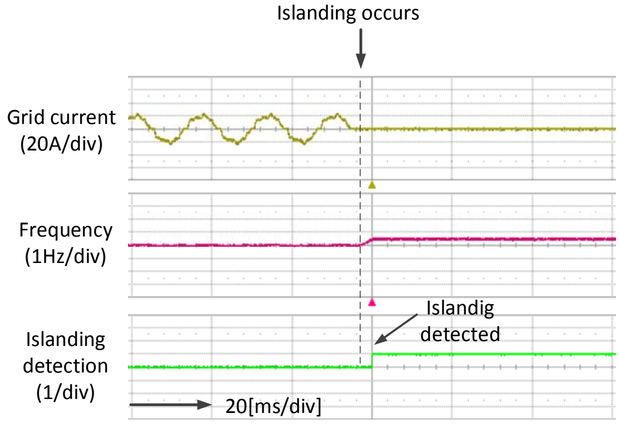


Fig. 20. Performance of the proposed islanding detection method in parallel operation with 10kW of P_{DG} and 5kW of P_{load}.

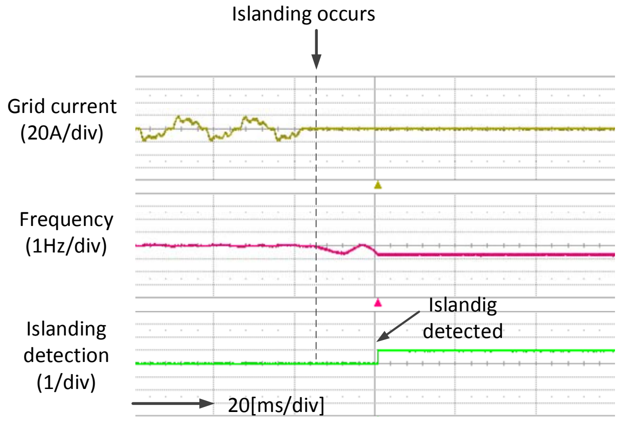


Fig. 21. Performance of the proposed islanding detection method in parallel operation with 5kW of P_{DG} and 10kW of P_{load}.

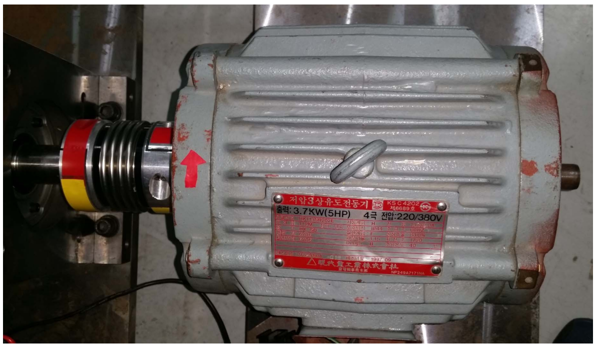


Fig. 22. Load induction motor.

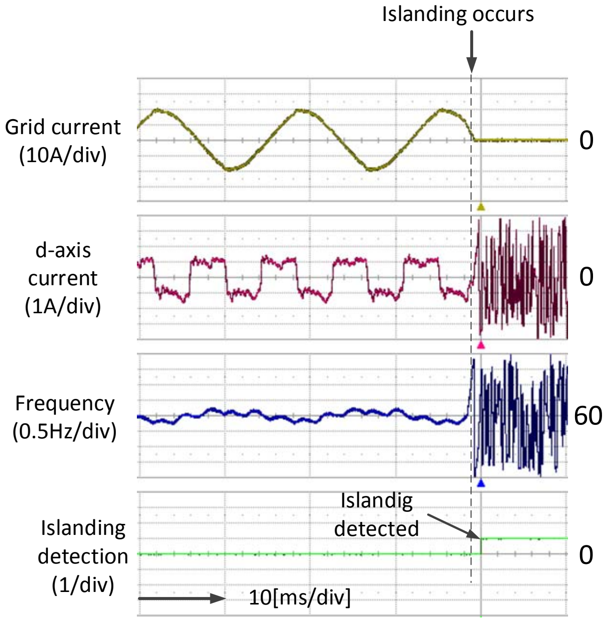


Fig. 23. Performance of the proposed islanding detection method under an induction motor

VII. CONCLUSIONS

In this paper, a bilateral reactive power injection method has been proposed for the islanding detection. The magnitude of the reactive power to be injected is derived to be 5.01% by considering the load condition specified in the standard such as IEEE Std. 929 and IEEE Std. 1547. The injection frequency is also determined to be a half grid frequency by considering the parallel operation of multiple converters in different distributed generation systems with no communication. The performance of the proposed method has been experimentally confirmed not only for a single converter but also for two converters with common DC source connected to a Li-ion battery bank. The proposed method is effective not only in the case of typical RLC loads defined in international standards for islanding detection but also in the case of a typical industrial load including an induction motor load.

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