Analysis of Non Detection Zone for Multiple Distributed PCS Based on Equivalent Single PCS Using Reactive Power Approach

Byeong-Heon Kim and Seung-Ki Sul
Dept. of Electrical and Computer Engineering
Seoul National University
Seoul, Republic of Korea
heon13@snu.ac.kr

***Abstract*— In this paper, the methodology to analyze Non-Detection Zone (NDZ) of islanding detection algorithm for multiple Power Conditioning Systems (PCSs) connected to grid is proposed. The PCSs with renewable energy source or battery energy storage system are equipped with anti-islanding functionality and the method using frequency positive-feedback is one of the most popular methods to detect islanding condition. Because it is figured out that the positive feedback of grid frequency is only valid on reactive current, not the phase of current or active current, the reactive power according to the frequency drift algorithm is only considered for NDZ analysis in the proposed analysis. Additionally, the reactive power component by frequency drift anti-islanding can be linearized in normal operation range of grid frequency. By incorporated with this concept, Equivalent Single PCS (ESPCS), which equivalently supplies whole reactive current of multiple PCSs, is proposed and this could emulate the operation of multiple parallel PCSs without loss of the detection capability. The NDZ is analyzed by ESPCS and is compared to the NDZ of parallel PCSs. Through the computer simulation and hardware experiments, it is confirmed that NDZ based on ESPCS and operation dynamics is well matched to those of multiple PCSs.**

Keywords—Anti-islanding; frequency drift; positive feedback; reactive power; multiple inverters; non-detection zone

I. INTRODUCTION

The islanding is defined as a condition where a portion of the utility power system, which is energized by one or more local electric power systems through the associated point of common coupling (PCC), is electrically separated from the remainder of utility power system [1], [2]. The anti-islanding function is the strategy to detect islanding condition by each distributed resource by hardware setup and/or software implementation. Because the islanding would cause a severe threat to the grid operation, anti-islanding functionality is mandatory feature for distributed power conditioning systems (PCSs) connected to the grid [1]-[3].

The anti-islanding scheme implemented in software of PCS can be classified as passive and active methods. Among active methods, the frequency drift method (FDM) based on positive-feedback by grid frequency is one of the most popular methods and equipped in many commercially available grid connected inverters [4]. The Active Frequency Drift (AFD), Sandia Frequency Shift (SFS) and Slip-Mode frequency Shift (SMS) are the representative algorithm for FDM, which are developed originally for single-phase photovoltaic (PV) applications. These methods control the phase of inverter output current, which is modulated by function of grid frequency. Because the frequency is drift away after islanding due to the positive feedback loop, the FDMs can detect islanding by triggering Over/Under Frequency (OUF) relay [5], which is the basic requirement of protection for grid connected PCSs [1]-[3]. The Non-Detection Zone (NDZ) for FDMs, which is the performance index for anti-islanding, is commonly depicted on load plane of quality factor and resonant frequency of islanding load with assuming that the load has passive components (parallel R, L, C) [5, 6].

The conventional phase criterion is a powerful tool to analyze the islanding operation of the inverter equipped frequency drift anti-islanding scheme. By the results on [7], the non-detection zone (NDZ) of multiple inverters can be analyzed. However, because of the complexity of phase relationship due to trigonometric functions, the equation for analyzing NDZ also becomes complex. This complexity increases as the number of PCSs connected to PCC is getting larger.

In this paper, an analysis method, which overcomes the complexity of phase criteria, has been proposed. In the previous literatures, it is figured out that the reactive power of PCS, not the phase of current of PCS, causes the frequency drift after islanding [4, 8-10]. And, for analyzing NDZ it is sufficient that reactive power component of current is considered. The reactive power of the PCS, which is caused by the frequency drift algorithm, can be represented by a linear polynomial under normal operation region of grid frequency. To analyze NDZ of multiple PCSs, the Equivalent Single PCS (ESPCS), which equivalently injects the whole reactive power made by whole PCS system, is proposed. By merging the linearized reactive components of each PCS to single reactive power, the whole PCSs can be emulated by an ESPCS. The NDZ of multiple PCSs also could be simply obtained through the proposed ESPCS concept and detail explanation is

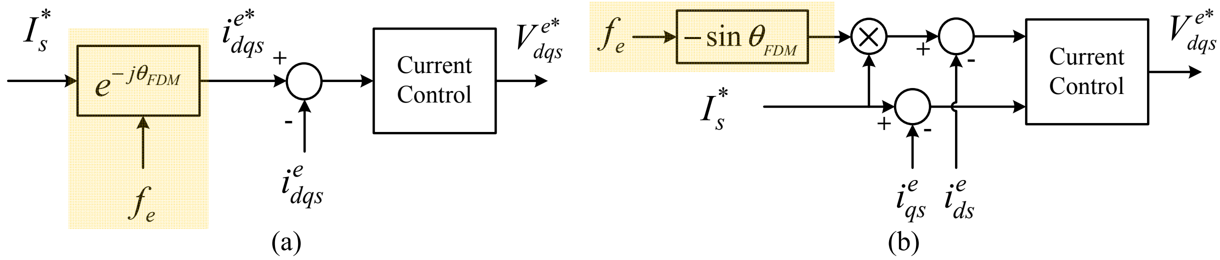


Fig. 1. Implementation of frequency drift anti-islanding in three phase system
(a) Simple rotation of current reference (b) Injection of reactive component only

demonstrated in followed sections. The computer simulation and experimental results show the effectiveness of proposed concept of ESPCS.

II. LINEARIZED REACTIVE POWER COMPONENT OF PCS BY FREUQENCY DRIFT ANTI-ISALDNING

In single-phase applications with constant current regulation, the magnitude and the phase of current are possible candidates to construct positive feedback loop. The conventional anti-islanding algorithm based on the frequency drift, such as AFD, SFS or SMS, uses the phase of current reference to build the frequency positive feedback loop. In three-phase system, the variation of current reference due to the phase made from anti-islanding can be represented as in (1) and (2). This variation leads to the rotation of the current reference vector as shown in Fig. 1 (a) [6, 10], with assumption that the power factor is controlled as unity.

$$i_{ds}^{e*} = -\sin\theta_{FDM} \times I_s^* \tag{1}$$

$$i_{qs}^{e*} = \cos\theta_{FDM} \times I_s^* \tag{2}$$

where, θ_{FDM} represents the phase function of current reference made by the frequency drift algorithms. And I_s^* represents the magnitude of original current reference produced by outer loop or reference generator. The current is represented in the synchronously rotating reference frame. In this paper, the *d*-axis component means the reactive power component and the *q*-axis component means the active power component. If the *q*-axis current has positive value, PCS supplies active power to the grid. For the *d*-axis current, capacitive current has positive value and inductive current has negative value.

In the conventional implementation, the frequency is fed-back to both active and reactive components. However, the relationship between the reactive power of PCS and the grid frequency after islanding is only reason of frequency drift as in [10]. That is, the only reactive component of current reference in (1) would drift frequency to outward of normal frequency range. In result, not active but reactive component should be injected for a positive feedback as shown in Fig. 1 (b). With using the injection of the reactive power component, the reactive power reference can be represented as (3). The equivalent reactive current reference is derived as (4).

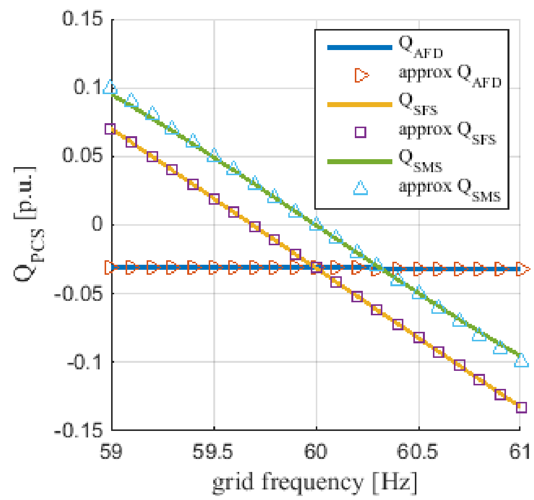


Fig. 2. Reactive power of PCS vs. Grid frequency

$$Q_{DG}^* = g\left(f_e - f_g\right)P_{DG}^* = -\sin\theta_{FDM} \times P_{DG}^* \tag{3}$$

$$i_{ds}^{e*} = g\left(f_e - f_g\right)I_s^* = -\sin\theta_{FDM} \times I_s^* \tag{4}$$

where, function noted by $g\left(f_e - f_g\right)$ represents the generalized form of the positive feedback anti-islanding. f_e represents the estimated grid frequency by phase-locked-loop (PLL) and f_g represents the nominal grid frequency.

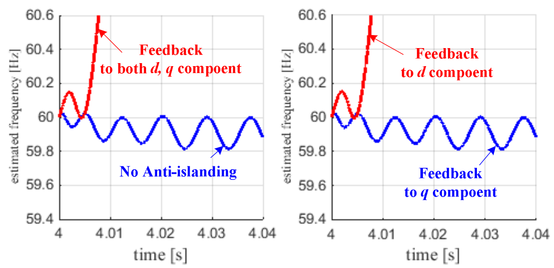
With Taylor series expansion of (3) and (4), (5) can be derived approximately representing the reactive power reference of PCSs. Because of linearity, high-order terms could be neglected.

$$Q_{DG}^* \approx \left[a_0 + a_1\left(f_e - f_g\right)\right]P_{DG}^* \tag{5}$$

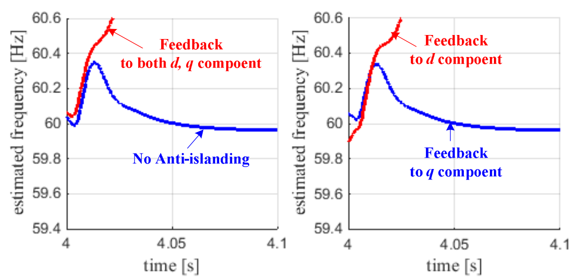
This approximation could be understood through the Fig. 2. In Fig. 2, several reactive power references for conventional method are plotted. In the Table 1, for several frequency drift algorithms, the phase function of current reference and equivalent coefficients of (5) are shown. The method using

Table 1. Coefficient of linearized reactive power of PCS

	θ_{FDM} [5]	a_0	a_1
AFD	$\pi f t_z$	$-\pi f_g t_z$	$-\pi t_z$
SFS	$\frac{\pi}{2}\left[cf_0 + k\left(f_e - f_g\right)\right]$	$-\frac{\pi}{2}cf_0$	$-\frac{\pi}{2}k$
SMS	$\theta_m \sin\left(\frac{\pi}{2}\frac{f_e - f_g}{f_m - f_g}\right)$	0	$-\theta_m \frac{\pi}{2\left(f_m - f_g\right)}$
PRI	-	$\begin{cases} K_1 & Period\,1 \\ K_2 & Period\,2 \end{cases}$	0



(a) Single phase PCS case



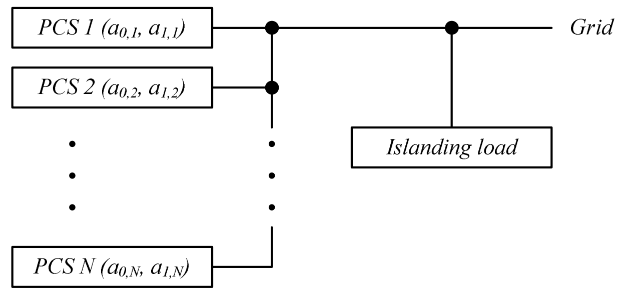
(b) Three phase PCS case

Fig. 3. Test of islanding detection capability with various feedback components

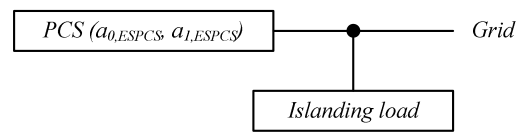
Periodic Reactive power Injection (PRI) is also represented [11]. These coefficients can be applied for the linearization of (4).

The Fig. 3 shows the simulation results of test of islanding detection capability with SFS algorithm. In the case of single-phase PCS, the active and reactive powers are decomposed by using *d-q* synchronous reference frame. Islanding has happened at 4 s. Both single phase and three phase, the feedback of the active power component cannot drift grid frequency under islanding condition and shows same dynamics to the result with no anti-islanding. The only positive feedback-loop to reactive component results frequency drift and can detect islanding condition.

That is, not the phase of current reference, but the reactive current can only drift the grid frequency with positive feedback.



(a) Multiple PCSs



(b) ESPCS

Fig. 4. Equivalent Single PCS to analyze NDZ

III. Analysis of Non-Detection Zone for Multiple Distributed PCSs by Equivalent Single PCS

In [7], for analyzing NDZ of Multi-PCSs, the phase of 'the equivalent active frequency drifting islanding detection method' is calculated. However, because of complexity of the relation between the each current of inverter, the equivalent phase becomes complex as number of inverters connected to the grid is getting larger. The main reason of this complexity is the trigonometric function. This complexity makes to extend the analysis to arbitrary number of inverters be difficult.

As discussions in the section II, in this paper, by considering only reactive current of each inverter, an Equivalent Single PCS (ESPCS) has been suggested and this alleviates the burden of adding other PCSs to the grid. Similar concept is already proposed in [4], and that has shown the performance of islanding detection for parallel inverters with same anti-islanding algorithm.

From the view of load or grid side, the multiple PCSs supply reactive power which is the sum of reactive power of each PCS in whole power system. It can be assumed that the ESPCS, which has same power capacity with total sum of the multiple PCSs, supply this whole reactive power equivalently. In Fig. 4, ESPCS representing multiple PCSs is depicted. Equation (6) represents the reactive power reference of the ESPCS. The subscript k represents index of each PCS.

$$Q^*_{DG,ESPCS} = \Sigma_k\left(\left[a_{0,k} + a_{1,k}\left(f_e - f_g\right)\right]P^*_{DG,k}\right) \tag{6}$$

If the power ratio of each PCS to whole PCSs is defined as the weighting factor, w_k , (6) can be rewritten as (7).

$$\begin{aligned} Q^*_{DG,ESPCS} &= \Sigma_k\left(w_k\left[a_{0,k} + a_{1,k}\left(f_e - f_g\right)\right]\right)P^*_{DG,ESPCS} \\ &= \left[\left(\Sigma_k w_k a_{0,k}\right) + \left(\Sigma_k w_k a_{1,k}\right)\left(f_e - f_g\right)\right]P^*_{DG,ESPCS} \\ &= \left[a_{0,ESPCS} + a_{1,ESPCS}\left(f_e - f_g\right)\right]P^*_{DG,ESPCS} \end{aligned} \tag{7}$$

Because of the linearity, the calculation of equivalent reactive power of ESPCS is much simpler than equivalent phase in [7]. In the case of not using frequency drift algorithm, for example, passive anti-islanding or other anti-islanding methods injecting current or voltage of arbitrary frequency, the weighting factor can be set to zero because the reactive power from that method is zero. This assumption is more intuitive than [7], which modifies the quality factor of islanding load considering the active power of inverter not using FDM.

To obtain NDZ on load plane, the convergent frequency after islanding should be identified. The frequency is the crossover point of reactive power curve of PCS and of islanding load. If the parallel RLC load is assumed, under islanding condition, the load has reactive power curve as (8). This could be linearized around operation frequency [8].

$$Q_{load} = P_{DG} Q_f \left(\frac{f_{res}}{f_{is}} - \frac{f_{is}}{f_{res}} \right) \approx -2 P_{DG} \frac{Q_f}{f_{res}} \left(f_{is} - f_{res} \right) \quad (8)$$

where, Q_f is the quality factor of islanding load and f_{res} is the resonant frequency of the load [1]. f_{is} is the grid frequency at the PCC after islanding.

From (7) and (8), with assumption of the reactive power matching between PCS and load under islanding, the crossover point can be calculated as (9).

$$f_{cross} = \left(a_{1,ESPCS} + 2 \frac{Q_f}{f_{res}} \right)^{-1} \left(-a_{0,ESPCS} + a_{1,ESPCS} f_g + 2 Q_f \right) . \quad (9)$$

With the crossover frequency, the instability condition is also considered [5, 8]. The instability criterion is given by (10). If this criterion is met, the grid frequency will be diverged after islanding and the islanding can be detected by OUF relay.

$$a_{1,ESPCS} < -2 P_{DG} \frac{Q_f}{f_{res}} \quad (10)$$

The NDZ for ESPCS can be defined as load condition that couldn't satisfy (10) and has the crossover frequency which resides in normal frequency range after islanding. This NDZ is based on steady-state concept. Based on (10), the gain of anti-islanding can be designed to detect islanding under given local load condition. When the additional PCS is installed, if the weighted feedback gain is enough to detect the islanding with the local load, then the additional PCS doesn't need to equip FDM. And, the existing PCS equipped the injection of reactive power could detect the islanding operation with the additional PCS.

IV. VERIFICATION

In Fig. 5, the conceptual diagrams of circuit used in simulation and experiment are depicted. For parallel PCSs, three independent PCSs are operated with local islanding load, while ESPCS is emulated by single PCS. Islanding condition is simulated by opening of the breaker connected to the grid.

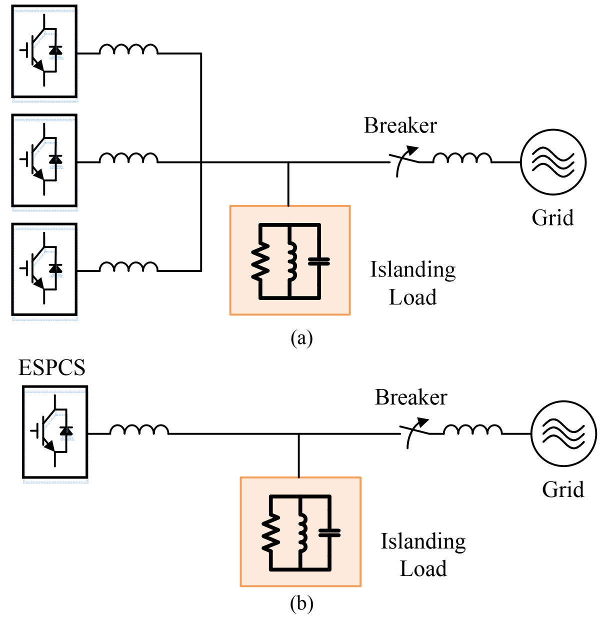


Fig. 5. Circuit diagram for verification

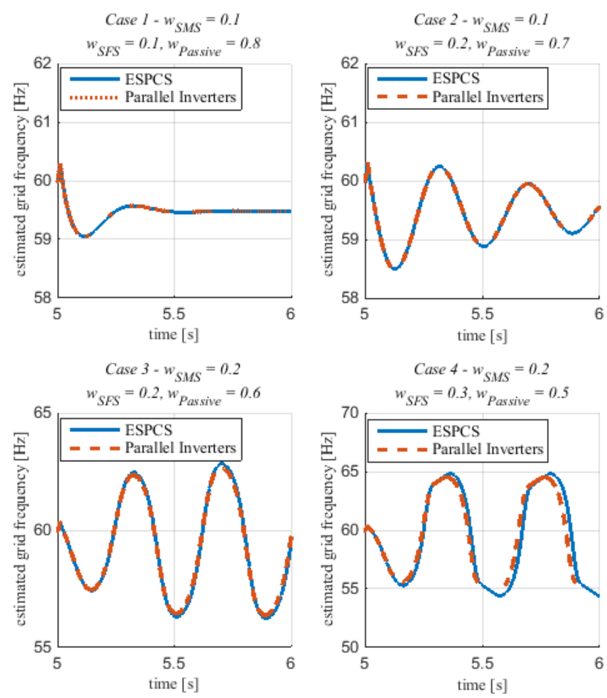


Fig. 6. Islanding test with various weighting factor

A. Simulation Results

By the computer simulation, three parallel-connected inverters and the single inverter with the proposed concept of ESPCS are under test. The control algorithms are implemented by Matlab/Simulink in discrete model and the electric circuit

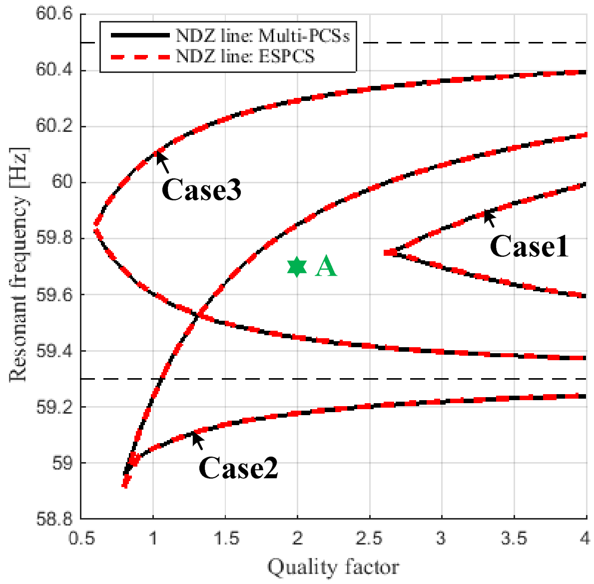


Fig. 7. NDZ for experimental setup

simulation is done by simulation language PLECS [12]. The trip function caused by software frequency relay is deactivated in simulation for observing the behavior of PCS frequency after islanding.

For three parallel-connected inverters, the SFS, SMS and passive method (voltage/frequency relay) are equipped in each PCS. Fig. 6 shows the result of islanding test. Islanding occurs at 5 s. The weighting factor for each case is represented in the title of each figure. The dynamics of current regulator is neglect and the same PLL algorithm in [13] is equipped.

Table 2. Weighting factor for case study

Case	AFD	SFS	SMS	Passive
1	0.1	0.6	0.3	0
2	0.7	0.2	0.1	0
3	0	0.1	0.1	0.8

As seen in all results of Fig. 6, the frequency drift property of ESPCS is well matched to that of three parallel inverters. In case 1 and 2, the estimated grid frequency is converged and islanding couldn't be detected. However, in another case, the estimated frequency has large oscillation and goes outward of the abnormal operation region would trip OUF relay.

That is, the PCSs operated in parallel can be replaced by an ESPCS whose capacity is same to the whole inverters and the NDZ of parallel PCSs can be easily identified through this ESPCS.

B. *Experimental Results*

To verify the discussions in section III, islanding test with the hardware experimental setup is carried on. The test circuit, which is commonly specified in international standards such as [1]-[3], is constructed. The total power of whole system is set to 5 kW. The islanding load contains three phase passive components (parallel R, L, C). The quality factor of islanding load in the experiment was set as 2; The 'A' point in Fig. 7 represents this load condition. Due to the component tolerance, the resonant frequency has been identified as 59.7 Hz.

For the condition used in experiment, the NDZ analyzed by ESPCS could be represented as Fig. 7. Each PCS is equipped with different anti-islanding methods. In Table 2, the weighting factor of each PCS for three cases is represented. For AFD, the

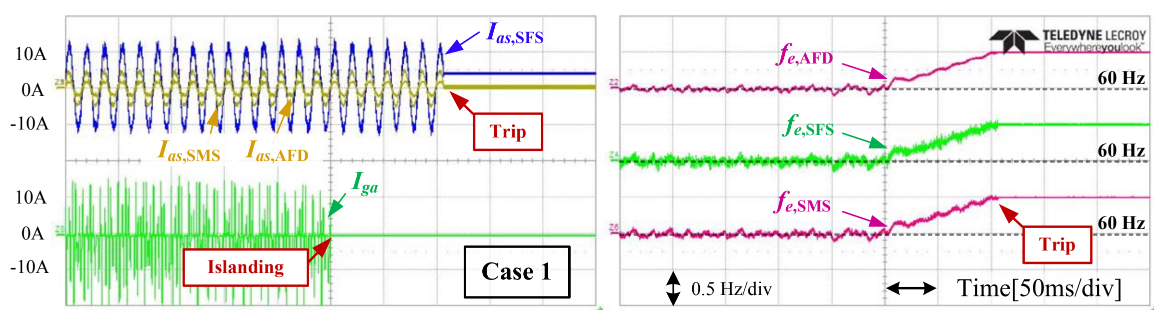


Figure 8. Experimental results – three PCSs (Case 1)

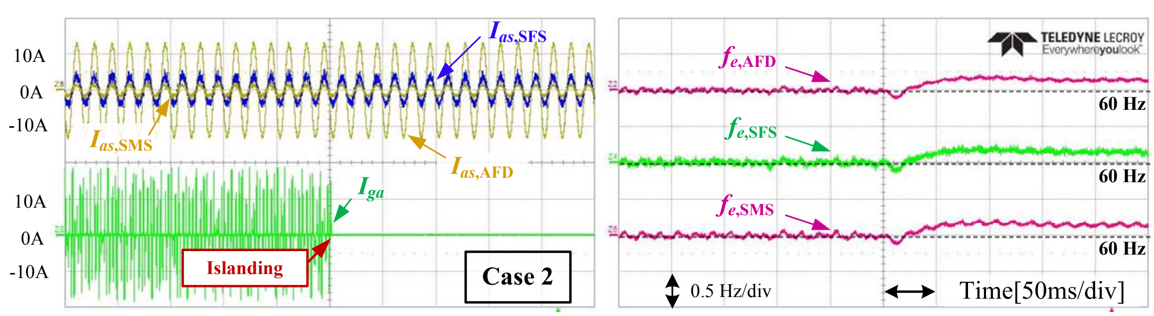


Figure 9. Experimental results – three PCSs (Case 2)

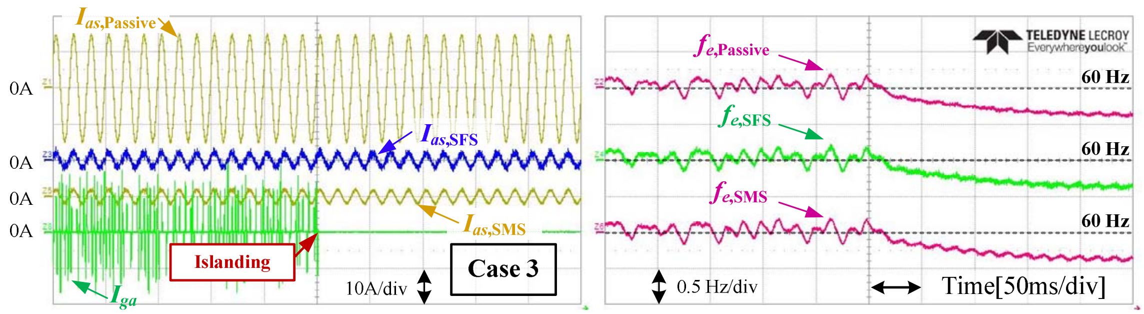


Figure 10. Experimental results – three PCSs (Case 3)

chopping factor is set to 0.02. The feedback gain of SFS and SMS is adjusted to detect islanding load with quality factor 3 when the PCS is operated separately. The weighting factors and positive feedback gain for case 2 and 3 are set not to be able to detect islanding condition under quality factor 2. And case 1 is set to detect islanding by FDM. For comparison, the NDZs simulated by multiple PCSs are also plotted. In Fig. 7, the NDZ of multiple PCSs obtained by the proposed ESPCS is overlaid and it is almost coincide with NDZ lines with Multi-PCSs.

The experimental results are shown in Fig. 8 ~ 13. Fig. 8 ~ 10 show the test results for the case of three parallel PCSs and Fig. 11 ~ 13 show the results for single PCS with reactive power made by proposed ESPCS concept. For showing the amount of active power mismatch, voltage magnitude at PCC is also plotted in result of ESPCS. Because the active power is adjusted to match, the PCC voltage after islanding varies under 10% with respect to the nominal value and this value is inside the normal voltage range. The frequency relay is triggered under 59.3 Hz or above 60.5 Hz that satisfies the international regulations.

According to the Fig. 7, the position of load condition on load plane doesn't reside in the NDZ for case 1 and it is expected to detect islanding for this case. And, Fig. 8 and Fig 11 clearly demonstrate that the frequency of both three PCS and ESPCS cases drift to trigger OUF relay due to the over frequency. Three parallel PCSs supply the weighted active current and total current is equal to that of ESPCS. Because the same PLL structure is adopted, the estimated frequencies in three parallel PCSs show same drift dynamics after islanding.

On the other hand, for the case 2 and 3, the load condition used in the experiments resides in the NDZs. As expected, the islanding couldn't be detected by anti-islanding and system continuously supplies power to load, because the reactive power slope is not large enough to drift frequency and the crossover frequency is in the normal operation region.

As experimentally verified, by proposed concept of ESPCS, the operation of multiple PCSs after islanding can be forecasted accurately.

V. CONCLUSION

In this paper, an analysis tool to investigate NDZ for multiple PCSs has been proposed. Based on the fundamental

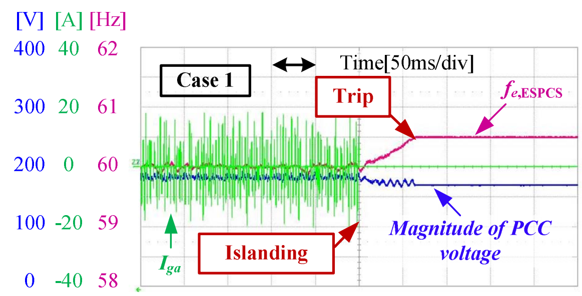


Figure 11. Experimental results – ESPCS (Case 1)

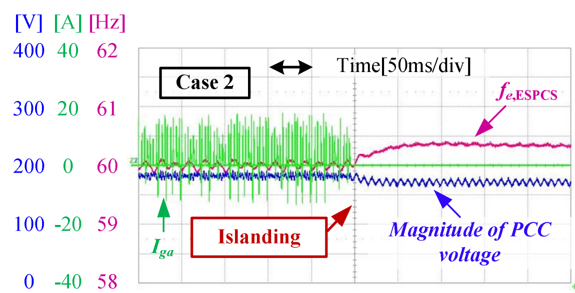


Figure 12. Experimental results – ESPCS (Case 2)

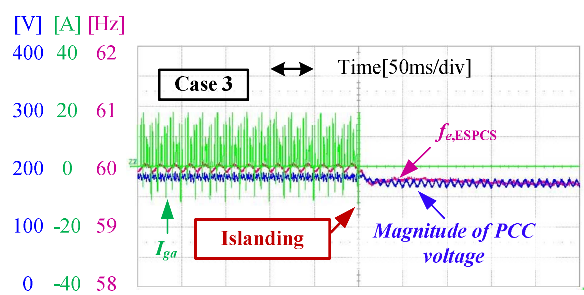


Figure 13. Experimental results – ESPCS (Case 3)

characteristics of the frequency drift, the only reactive power components of each PCS are considered to analyze NDZ. These reactive power components of each PCS are summed and represented by an ESPCS which supply this total sum of the reactive power. To sum the reactive power effectively, the reactive power produced by the frequency drift is linearized and it is shown that this linearization is valid on the normal operation region of grid frequency. The coefficient of linear function for conventional FDM also calculated. This approximation has made summing up of the reactive power of each PCS without trigonometric function possible and reduces the burden of computation compared to phase criteria.

With linearized reactive power of the islanding load, the NDZ of ESPCS was also obtained by the instability criterion and the crossover frequency after islanding. This NDZ can emulate the NDZ of parallel PCSs. Through the instability criterion, the setting of the feedback gain to detect islanding under given local load would be possible.

The results of the simulation and experiment have confirmed that the proposed ESPCS can emulate the operation and the NDZ of the multiple PCSs accurately.

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