Design Consideration and Performance Analysis of a Hybrid Islanding Detection Method Combining Voltage Unbalance/Total Harmonic Distortion and Bilateral Reactive Power Variation

Gongke Wang, Feng Gao, Jiaxin Liu, Qiying Li, and Yong Zhao

***Abstract*—This paper proposes a hybrid islanding detection method for inverter-based distributed generation units. Firstly, this paper carries out a comprehensive characteristic analysis and obtains design principles for the hybrid method in inverter-based DGs. Then, based on these principles, the proposed method combines the passive method of voltage unbalance and total harmonic distortion (VU/THD) detection and the active method of bilateral reactive power variation (BRPV). In specific, the BRPV method is only triggered when the islanding condition is suspected by VU/THD method. Doing so, the islanding detection performance can be improved significantly without reducing the power quality. In addition, this paper modifies the conventional VU/THD method to realize fast and accurate detection, and the threshold setting principle is analyzed for the first time based on equivalent circuit approach. Comparison analysis reveals that the proposed method has a more satisfactory islanding detection performance for inverter-based distributed generation units. Simulation and experimental results under various conditions based on IEEE Std. 929 and IEEE Std. 1547 were carried out to verify the islanding detection performance of the proposed method.**

***Index Terms*—Distributed generation unit, hybrid method, islanding detection.**

I. Introduction

THE inverter-based distributed generation (DG) units, which utilize renewable energy, e.g., photovoltaic, wind power, fuel cell, etc., have been widely implemented in recent years [1], [2]. In order to ensure the safe operation of both utility and DGs, the DGs have to be equipped with islanding detection function according to IEEE Std. 929-2000 [3] and IEEE Std. 1547-2003 [4] because islanding may cause the voltage and frequency to vary significantly and bring hazards to electrical equipment and utility maintenance personnel [5]–[10]. Thus, many islanding detection methods were proposed to detect the islanding condition timely, which can be divided into three main categories: communication-based methods, passive methods, and active methods [5], [6].

There were some communication methods proposed for islanding detection, such as power line carrier communication method, which have to implement the transmitter capable of sending signals into the utility system [6], [7]. As a consequence, these methods have not been widely adopted due to the high cost.

Passive islanding detection methods detect the islanding condition by monitoring parameters' change at the point of common coupling (PCC). There are some typical passive methods such as under/over voltage method [8], under/over frequency method [9], voltage phase jump detection method [10], rate of change of frequency (ROCOF) protection method [11] and the voltage unbalance and total harmonic distortion (VU/THD) method [12]. Passive methods can detect the islanding condition timely and will not cause any disturbance, but they have a common drawback which is the difficulty of threshold setting. Sensitive settings may cause nuisance trips, otherwise, non-detection zone (NDZ) would be large, which means the detection method may fail when the power mismatch is small.

In order to overcome the limitation of passive methods, active methods were developed. In specific, active methods detect the islanding condition by introducing perturbations to the grid and monitoring the parameters of PCC at the same time. The parameters monitored are sustained by the grid under grid-connected mode, but they will drift out of the allowed range because of the perturbations introduced when operating under islanding mode. The active frequency drift (AFD) method [13], Sandia frequency shift (SFS) [14], slip mode frequency shift (SMS) method [15], Sandia voltage shift (SVS) method [16] and reactive power variation (RPV) method [17] are typical active methods. In comparison, active methods have a relatively small NDZ, but the power quality would be deteriorated as these methods introduce perturbations to the grid continuously. And when considering the inverters' count increases significantly in the grid, the active islanding detection methods are likely to fail when parallel connected inverters

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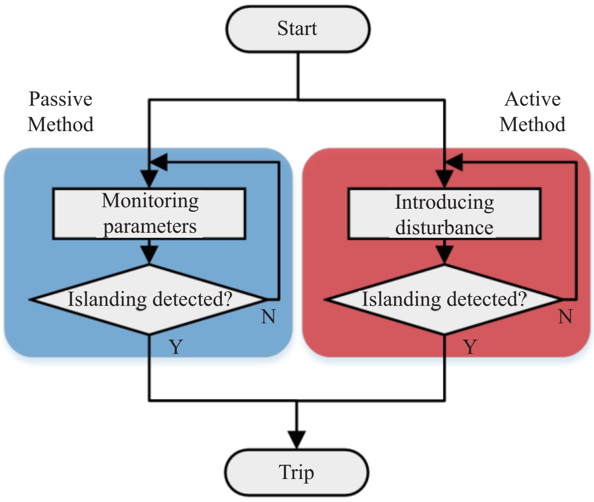

Fig. 1. Operational principle for the combination of passive method and active method in parallel mode.

inject their own disturbance signals independently [18]–[20]. For instance, when some inverters inject perturbations to make the PCC frequency drift up while the others cause the frequency to drift down, they will counteract each other and affect the islanding detection performance.

As passive methods and active methods have their own strengths, they are typically combined together in parallel mode as shown in Fig. 1 to improve the islanding detection accuracy [5]. However, this combination mode also combines the weaknesses of the passive methods and active methods, it will cause nuisance trip if a sensitive passive method is adopted, and the perturbation and counteraction problems caused by active method are also not solved.

Therefore, the perturbation introduced and counteraction between inverters are the two problems of great concern in inverter-based islanding detection technique. To deal with the counteraction problem, several new methods were proposed, such as the online grid impedance measurement [18], master-slave strategy [19] or external centralized disturbances injection [20], but they all need cooperation between inverters and increase the operation complexity. Besides, the perturbation problem was not considered in these methods.

While the hybrid method, which is simple to implement and can work independently, can solve these problems with proper design. This method combines the passive method and active method in series mode as shown in Fig. 2, where the active method is only triggered when the islanding condition is suspected by the passive method [21]. Doing so, this method is able to eliminate the counteraction between inverters as the active method can be synchronously triggered by the passive method. And the NDZ and the perturbation of hybrid method can be optimized with the proper design. Several hybrid methods have been proposed in previous literatures [21]–[23]. However, up to now, the design principles has not been elaborated comprehensively and these hybrid methods demonstrate some limitations, which will be elaborated in Section II.

Therefore, this paper makes a comprehensive characteristic

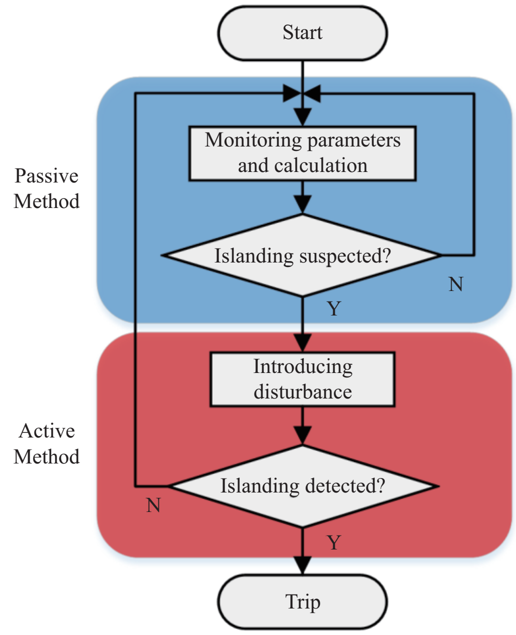

Fig. 2. Operational principle of hybrid method.

analysis and derives the design principles which can guide the hybrid method design of inverter-based DGs. And based on the design principles, a hybrid method, which utilizes voltage unbalance and total harmonic distortion (VU/THD) technique as the passive method and bilateral reactive power variation (BRPV) as the active method, is proposed. In specific, the BRPV method is only triggered when the islanding condition is suspected by VU/THD method. In addition, with the proper parameters design, NDZ of BRPV method can be eliminated when quality factor of local load $Q_f \leqslant 2.5$ according to the requirements in IEEE Std. 929 and IEEE Std. 1547. So, this method can avoid the power quality deterioration and work properly in multiple inverters system. Simulation and experimental results verified the performance of the proposed method.

This is an extension of the previous work in [24], and the major contributions of this paper are outlined as follows:

i) Based on the design principles derived, a new hybrid method with better performance is proposed. In addition, detailed analysis and many simulation and experimental tests have been done to show the strength and verify the effectiveness of the proposed method.

ii) This paper modifies the conventional VU/THD method to realize fast and accurate detection, and the threshold setting principle is analyzed for the first time based on equivalent circuit approach.

II. Design Principle of the Hybrid Method

To design a hybrid method with satisfactory performance, it is necessary to fully understand its characteristics in the first place. Table I summarizes the characteristics of passive method and active method respectively. In the hybrid method, the active method is only triggered when islanding condition is suspected by the passive technique, and the tripping

TABLE I
CHARACTERISTICS OF PASSIVE METHOD AND ACTIVE METHOD

	Passive method	Active method
Advantages	1. Fast detection speed 2. No disturbance	1. Small non-detection zone
Drawbacks	1. Difficulty in threshold Setting	1. Low detection speed 2. Disturbance 3. Counteraction in multiple inverters

operation is finally done by the active method. Doing so, the characteristics of the hybrid method are as follows:

i) The NDZ is the union of the NDZs of passive method and active method, since any system condition falls into NDZ of passive method or active method will cause the final failure of detection.

ii) The perturbation can be reduced significantly because the active method is only implemented when islanding condition is suspected by the passive method instead of implementing continuously.

iii) The detection time can be much shorter than that of active methods which are implemented periodically because the active method is triggered just after the islanding condition is suspected by passive method.

iv) The operation of active method can be synchronized by the passive method, so the counteraction problem between inverters can be solved in multiple inverters system.

Among these characteristics, characteristic (iv) is the common characteristic as it is determined by the structure of the hybrid method, while the NDZ, perturbation and detection time can be optimized with proper design.

Thus, it should be noted that a random combination of passive method and active method cannot achieve the satisfactory performance. And some combination methods are not suitable for inverter-based DGs. There're some hybrid methods proposed in previous literatures:

Method 1 Voltage Unbalance Technique and Positive Feedback Technique

This hybrid method was proposed for synchronously rotating DGs [21]. The positive feedback technique will change the output frequency 1.5 s every time when the islanding condition is suspected by the VU technique. It should be noted that the active method which detects islanding condition by frequency drift will introduce a large perturbation. Thus, this combination will reduce the power quality.

Method 2 Average Rate of Voltage Change and Real Power Shift

These two methods are utilized together initially for combined heat and power [22]. As real power shift has to change the active power generation, it is obviously not suitable for inverter-based DG.

Method 3 Rate of Change of Frequency (ROCOF) and Optimized SFS

This hybrid method was introduced in [23] for inverter-based DG. While the ROCOF method was initially proposed for islanding detection of synchronous generator (SG) based DG, which may fail when the power mismatch is quite small [11], and the optimized SFS method also introduces large perturbation on power quality, which will be more serious in multiple inverters system [25], [26].

Therefore, to realize the satisfactory performance in inverter-based DGs, design principles need to be derived from the above characteristics:

i) The obvious basic requirement is that both of the adopted passive method and active method should be simple to implement in inverter-based DG.

ii) To eliminate the NDZ, the passive method should be sensitive enough to identify the islanding mode and the active method should be able to eliminate the NDZ according to the requirements. Even though this may cause nuisance pre-detection in some cases, it will not cause nuisance trip as the tripping operation is finally done by active method.

iii) To further reduce the disturbance, the active method should bring in as less disturbance on the power quality as possible.

iv) Because the total detection time is determined by the active method, the detection time of active method should be relatively short.

These principles can guide the hybrid method design of inverter-based DGs. And based on these design principles, the proposed hybrid islanding detection method utilizes VU/THD method as passive method, which is known as a very sensitive passive detection method [21], [27]. And BRPV method, which can eliminate NDZ without introducing any harmonic components [28], is adopted as active method.

III. PROPOSED HYBRID ISLANDING DETECTION METHOD

The recommended system structure for islanding detection, according to IEEE Std. 929 and IEEE Std. 1547, is shown in Fig. 3, where the inverter, local load represented by paralleled RLC, and the grid are connected together at the PCC and the breaker is used to simulate the occurrence of the islanding condition. The resonance frequency of parallel RLC load has been tuned to the local utility operating frequency since this is assumed to be the worst-case scenario for successful detection of unintentional islanding. According to the standard requirements, the method should be able to detect the islanding condition with quality factor of local load $Q_f \leqslant 2.5$ [3], and the detection time should be shorter than 2s [4], [29]. The assumed passive method, active method and their hybrid operation method will be elaborated below, respectively.

A. Voltage Unbalance and Total Harmonic Distortion Method

The passive method adopted in the proposed hybrid method is the voltage unbalance and total harmonic distortion (VU/THD) detection method. This technique was introduced in [12], and it is known as a very sensitive passive detection method which may cause nuisance trip in some situations [21], [27].

This paper modifies the conventional VU/THD method to get better performance. Firstly, the positive and negative sequence components of PCC voltage are obtained by decoupled

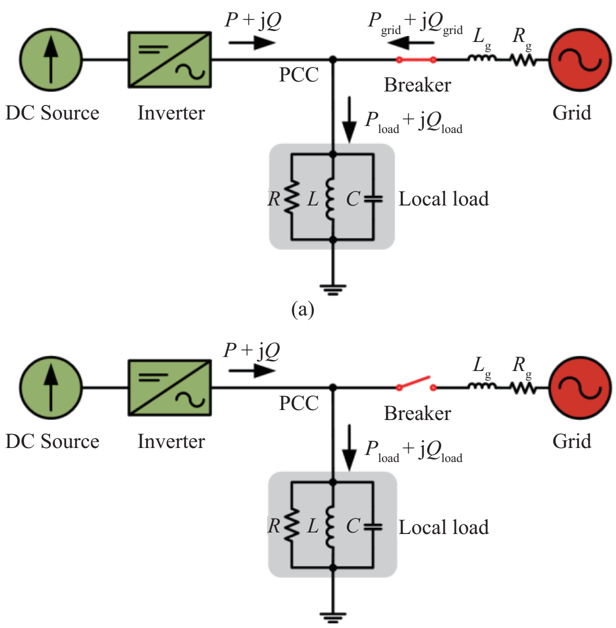

Fig. 3. General structure of inverter-based distributed generation system under (a) grid-connected operation mode and (b) islanding operation mode.

double synchronous reference frame PLL, which has the good dynamic response [30]. And a low-pass filter is used to avoid inaccurate detections caused by normal voltage fluctuation. Consequently, the detection sensitivity can be increased. Secondly, the conventional VU/THD method monitors VU and the current THD at the same time, but it was found that the VU is more sensitive to disturbances than current THD [21]. So, the voltage THD is monitored instead in the proposed method. Therefore, the modified VU/THD in this paper has better performance compared with the conventional algorithm.

Generally, the three-phase DG unit will power many different kinds of single-phase loads, so it is likely that the loss of main grid will cause the three-phase voltages unbalance. Furthermore, even though the load consumption and DG generation are closely matched, the voltage unbalance varies with the changes of network topology and interactions between different controllers (e.g., the dc-link voltage and the current controllers) [12], [27]. In specific, VU can be defined as

$$\mathrm{VU} = \frac{V_{\mathrm{NS}}}{V_{\mathrm{PS}}} \times 100\% \tag{1}$$

where, V_{PS}, V_{NS} are the magnitude of positive and negative sequences components of the PCC voltage. And the VU deviation is defined as

$$\Delta\mathrm{VU} = \frac{\mathrm{VU}_t - \mathrm{VU}_{t\text{-}d}}{\mathrm{VU}_{t\text{-}d}} \times 100\% \tag{2}$$

where, VU_t is the voltage unbalance at present moment, and $\mathrm{VU}_{t\text{-}d}$ is the value at a fundamental cycle before, d is set as one fundamental cycle.

In general, harmonics are generated by inverters due to the pulse width modulation, nonideal switching behaviors of the power devices and also the interaction among different controllers [31]–[33]. When the inverter works at the grid-connected mode, the harmonic currents produced by the inverter will flow out into the low-impedance grid to produce only a very small amount of distortion in the PCC voltage. But when the grid disconnects, the harmonic currents will flow into the local loads, which in general have much higher impedance than the grid. Thus, this produces large harmonics in the PCC voltage. The voltage THD is defined as

$$\mathrm{THD} = \sqrt{\sum_{h>1}^{H} V_h^2} \Big/ V_1 \times 100\% \tag{3}$$

where, V_h is the rms value of harmonic components and V_1 is the rms value of fundamental component. And the THD deviation is defined as

$$\Delta\mathrm{THD} = \frac{\mathrm{THD}_t - \mathrm{THD}_{t\text{-}d}}{\mathrm{THD}_{t\text{-}d}} \times 100\% \tag{4}$$

where, THD_t is the instantaneous value at present moment, and $\mathrm{THD}_{t\text{-}d}$ is the value at a fundamental cycle before.

VU/THD method uses a threshold of the deviation ΔVU/ΔTHD as detection criterion, and the inverter will trip when the threshold of ΔVU or ΔTHD is exceeded, which has a high sensitivity [12]. However, the threshold setting principle of this method has not been analyzed so far. Therefore, a comprehensive analysis is performed in Subsection II-C, and based on the analysis, the threshold of VU/THD method in the proposed hybrid method is properly designed.

The drawback of this method is that it may cause nuisance trip under large load switching or non-linear load integration even though the DG is connected to the utility [21], but it is suitable to be adopted as the passive method in the hybrid method due to its superior pre-detection capability.

B. Bilateral Reactive Power Variation Method

In general, the reactive power variation (RPV) method is a very attractive active method, because it is simple to be implemented and will not introduce any harmonic components [28]. This method controls the inverter to output sufficient reactive power, and drift the PCC frequency out of the permitted range consequently. Many RPV methods have been proposed in literatures, among which the intermittent bilateral reactive power variation (BRPV) method proved to be able to eliminate the NDZ with negligible effect on power quality [28]. The intermittent BRPV method changes the amplitude of the output reactive power between positive valve Q_{dis}, negative valve $-Q_{\mathrm{dis}}$ and 0 periodically as shown in Fig. 4, thus reducing the reactive power perturbation time and improving the power quality. And the NDZ of this method can be calculated as follows.

As shown in Fig. 3(a), when the DG is connected to the utility, the active and reactive power consumed by the local load can be represented as

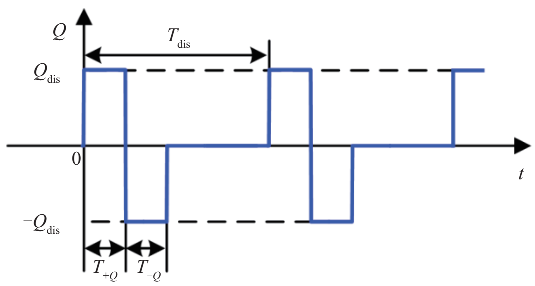

Fig. 4. Schematic diagram of intermittent bilateral reactive power variation.

$$P_{\text{load}} = P + P_{\text{gird}} = 3\frac{V_{\text{PCC}}^2}{R} \tag{5}$$

$$Q_{\text{load}} = Q + Q_{\text{gird}} = 3V_{\text{PCC}}^2\left(\frac{1}{2\pi fL} - 2\pi fC\right) \tag{6}$$

where, V_{PCC} and f are the voltage and frequency of the PCC, P and Q are the output active and reactive power of the inverter, and R, L, C represent resistance, inductance and capacitance of the local load, respectively.

The resonance frequency f_0 and quality factor Q_{f} can be defined as

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{7}$$

$$Q_{\text{f}} = R\sqrt{\frac{C}{L}} \tag{8}$$

By combining (5) and (6), the relationship between the system frequency in grid-connected operation mode and the characteristics of the RLC load can be derived as

$$f = \frac{f_0}{2}\left[\sqrt{\left(\frac{Q_{\text{load}}}{Q_{\text{f}}P_{\text{load}}}\right)^2 + 4} - \frac{Q_{\text{load}}}{Q_{\text{f}}P_{\text{load}}}\right] \tag{9}$$

Similarly, the frequency in the islanding condition is

$$f_{\text{is}} = \frac{f_0}{2}\left[\sqrt{\left(\frac{Q}{Q_{\text{f}}P}\right)^2 + 4} - \frac{Q}{Q_{\text{f}}P}\right] \tag{10}$$

Thus, the frequency after islanding can be drifted out of the allowed range by changing the amplitude of reactive power. Combining (9) and (10), the islanding frequency can be derived as

$$f_{\text{is}} = \frac{f}{4}\left[\sqrt{\left(\frac{Q_{\text{load}}}{Q_{\text{f}}P_{\text{load}}}\right)^2 + 4} + \frac{Q_{\text{load}}}{Q_{\text{f}}P_{\text{load}}}\right] \times \left[\sqrt{\left(\frac{Q}{Q_{\text{f}}P}\right)^2 + 4} - \frac{Q}{Q_{\text{f}}P}\right] \tag{11}$$

Assuming the frequency range is $[f_{\min}, f_{\max}]$, the NDZ can be derived from (11) as

$$Q_{\text{f}}\left(\frac{f_{\min}\sigma}{f} - \frac{f}{f_{\min}\sigma}\right) \leqslant \frac{\frac{Q_{\text{load}}}{P}}{\frac{P_{\text{load}}}{P}} \leqslant Q_{\text{f}}\left(\frac{f_{\max}\sigma}{f} - \frac{f}{f_{\max}\sigma}\right) \tag{12}$$

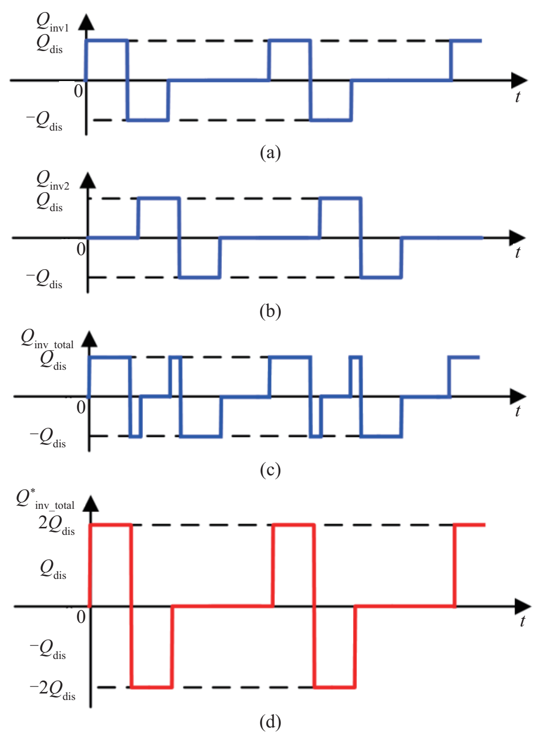

Fig. 5. Counteraction illustration of BRPV in multiple inverters system with (a) reactive power output of inverter 1, (b) reactive power output of inverter 2, (c) total reactive power output of two inverters and (d) ideal reactive power output sufficient for islanding detection.

where,

$$\sigma = \frac{1}{2}\left[\sqrt{\left(\frac{Q}{Q_{\text{f}}P}\right)^2 + 4} + \frac{Q}{Q_{\text{f}}P}\right] \tag{13}$$

According to (12), the NDZ of BRPV is composed of two parts. When the reactive power $Q = Q_{\text{dis}}$, the NDZ can be expressed as Z_{+Q}, and the NDZ can be expressed as Z_{-Q} when $Q = -Q_{\text{dis}}$, so the final NDZ of the system would be the overlapping area between Z_{+Q} and Z_{-Q}. To eliminate the NDZ of BRPV, Z_{+Q} and Z_{-Q} should not overlap. So according to (12), the variation amplitude Q_{dis} of reactive power should fulfill

$$Q_{\text{dis}} > \frac{f_{\max} - f_{\min}}{\sqrt{f_{\max}f_{\min}}}Q_{\text{f}}P \tag{14}$$

Thus, the NDZ of BRPV can be eliminated by designing parameters properly without introducing any harmonic components, so it is very appropriate for inverter-based DGs. However, the BRPV method also has the drawback which is the counteraction in multiple inverters system. The counteraction of intermittent BRPV is illustrated in Fig. 5, it can be seen that the perturbation of output reactive power will be degraded, thus causing detection failure. But this problem can be solved when adopted as the active method in a hybrid method.

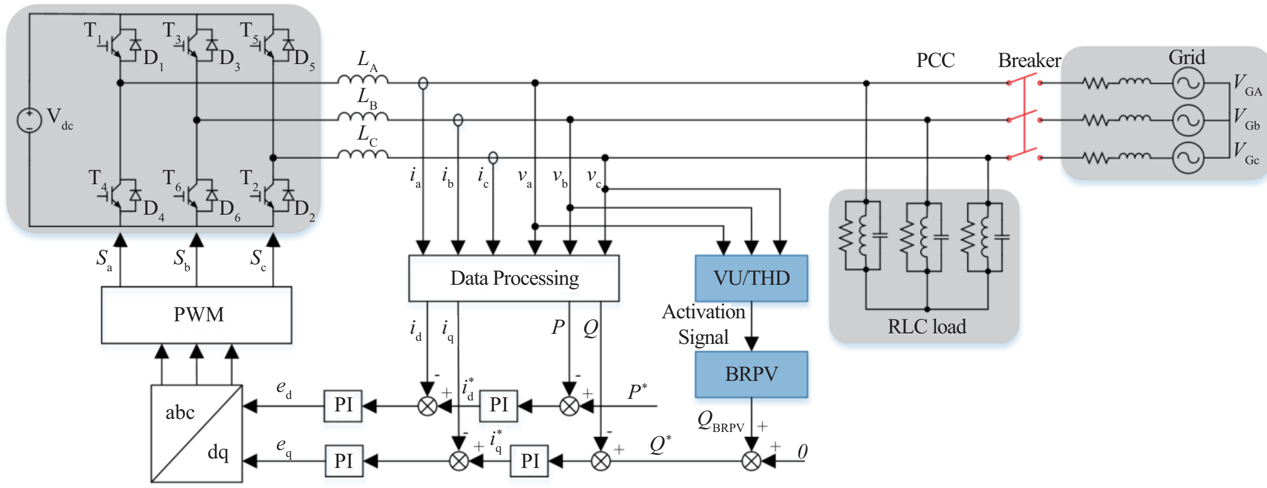

Fig. 6. Block diagram of the proposed hybrid method in an inverter control scheme.

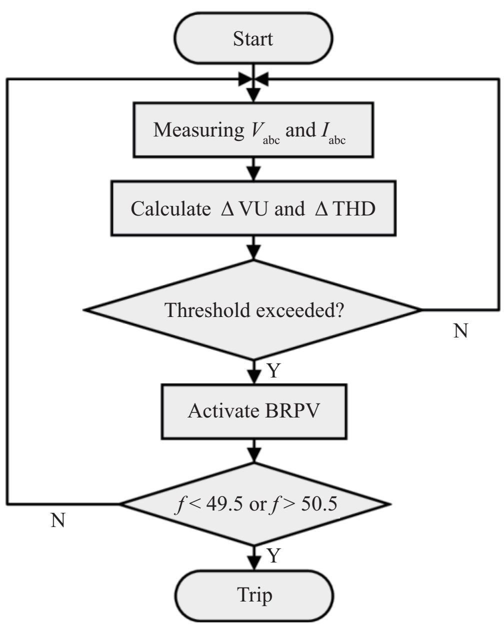

Fig. 7. Flowchart diagram of the proposed hybrid method.

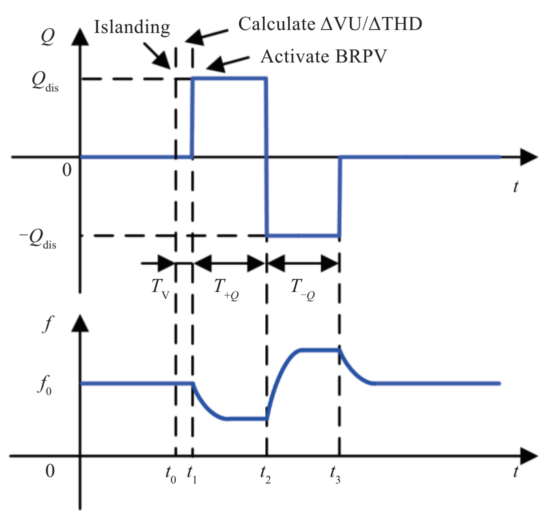

Fig. 8. Procedure illustration of the proposed hybrid method.

C. Hybrid Operation

According to the above analysis, the VU/THD method and BRPV method are both suitable to be used in hybrid method. Therefore, in the proposed method, they are combined together to get a satisfactory performance for inverter-based DG. And the block diagram of the proposed method in an inverter control scheme is shown in Fig. 6. The detailed analysis will be elaborated below.

1) Operation Principle

The flowchart diagram of the proposed hybrid method is illustrated in Fig. 7. In specific, the PCC voltage is monitored continuously, and the deviation of VU and THD over one cycle are calculated. When the threshold of ΔVU or ΔTHD is exceeded, the BRPV method will be activated. And in the proposed hybrid method, the BRPV method only needs to change the amplitude of the output reactive power between Q_{dis} and $-Q_{dis}$ once when it receives activation signal instead of working periodically as conventional way. Then, if the DG works at islanding mode, the frequency will drift out of the permitted range with the properly designed parameters, and the inverter will be shut down consequently. Otherwise, the inverter will still work at the normal state.

To clearly demonstrate the operational principle, the procedure illustration of the proposed hybrid method is shown in Fig. 8. The islanding happens at t_0, and the islanding condition is suspected by the VU/THD method at t_1 when the ΔVU/ΔTHD threshold is reached after a time duration T_V. Then the BRPV is activated at the same time to change the output reactive power, and the frequency will drift out of the permitted region consequently. Once the frequency reaches the threshold, the DG will be shut down immediately. And Fig. 9 presents the synchronous operation of multiple DGs, it can be seen that the

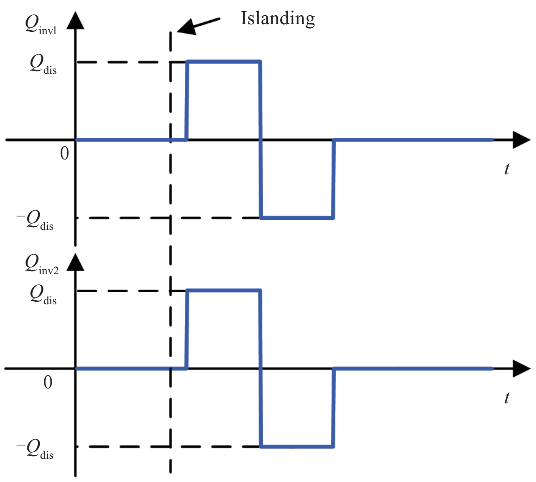

Fig. 9. Illustration of synchronous operation in multiple inverters DGs.

reactive power variations in both inverters are synchronized, so there will not be counteraction between inverters.

Many local load operations, such as large load switching and non-linear load integration, may cause the over-threshold of VU/THD method and the BRPV method will be activated consequently. Gird faults that do not island the DG may also cause large voltage and reactive power variations, then causing the over-threshold of VU/THD method and activation of the BRPV method. But it should be noted that the islanding detection is finally decided by the frequency in the proposed hybrid method. And the frequency behavior is irrelevant in these events because frequency is a global variable and not dependent on local events that cause a voltage or reactive power variation. Thus, the proposed method will not malfunction in these situations.

Therefore, as long as the inverter still connects to the grid and the grid frequency remains in the specified range of standards, the proposed method will not cause nuisance trip.

To conclude, the proposed method has characters as follows:

i) The proposed method can avoid nuisance trip under events that do not island the DG, as when the islanding is suspected by VU/THD method, it will further activate the BRPV method to detect the system frequency instead of tripping at once.

ii) The VU/THD method can identify the islanding condition immediately after the loss of main grid and the BRPV is activated at once, so the detection time is very short.

iii) The proposed hybrid method dose not introduce harmonic components and only has negligible impact on the power factor when BRPV method is activated.

iv) As the BRPV method is only implemented when the islanding condition is suspected by the VU/THD method, the BRPV method can be synchronized by the trigger signal from VU/THD method, thus the hybrid method can work properly in multiple inverters system.

2) Parameters Design

Up to now, the threshold setting principle of VU/THD method has not been deeply analyzed. Thus, this paper analyzes the threshold design based on equivalent circuit approach for the first time.

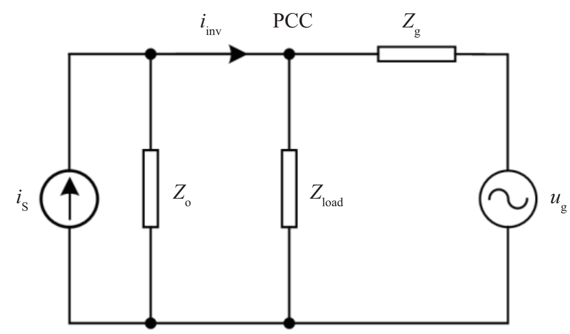

Fig. 10. Equivalent circuit of the grid-connected inverter.

The threshold of the passive method in the hybrid method is set as

$$\Delta \mathrm{VU} > 50\% \quad \text{or} \quad \Delta \mathrm{THD} > 100\% \tag{15}$$

For the VU deviation analysis, when isolated from the grid, there will be three system conditions: i) The three-phase DG unit powers different kinds of single-phase loads, and this will easily cause the ΔVU much larger than 50%. ii) The three-phase DG unit powers the same kinds of single-phase loads but the power mismatch is large, and in this case, the frequency will drift out of the allowed range after islanding. iii) The most critical condition for islanding detection is that the DG unit powers the same kinds of single-phase loads and the power mismatch is small. And in this case, the expression of ΔVU is derived as follows.

The equivalent circuit of the grid-connected inverter is shown in Fig. 10. The inverter is expressed by a Norton equivalent circuit, where the current source i_s is in parallel with the inverter output impedance Z_o. And the grid is expressed by a Thevenin equivalent circuit, where the ideal voltage source u_g and the grid impedance $Z_g = R_g + jX_g$ are in series. And the inverter output current can be decomposed as

$$i_{\mathrm{inv}} = i_{\mathrm{PS}} + i_{\mathrm{NS}} \tag{16}$$

where, i_{PS} and i_{NS} are the positive sequence current and negative sequence current respectively, thus the negative sequence PCC voltage under grid-connected mode can be derived as

$$v_{\mathrm{NS}} = \frac{Z_g Z_{\mathrm{load}}}{Z_g + Z_{\mathrm{load}}} i_{\mathrm{NS}} \tag{17}$$

At the instant of islanding happens, the current can be considered to be constant. Thus, the negative sequence voltage of PCC after islanding is

$$v'_{\mathrm{NS}} = Z_{\mathrm{load}} i_{\mathrm{NS}} \tag{18}$$

When the power mismatch is small, the deviation of positive sequence voltage Δv_{PS} will be much smaller than v_{PS} when islanding happens, so the positive sequence PCC voltage after islanding will be $v'_{PS} \approx v_{PS}$, and ΔVU at the time when islanding happens can be presented as

$$\Delta VU = \frac{\left|v'_{NS}\right| / \left|v'_{PS}\right| - \left|v_{NS}\right| / \left|v_{PS}\right|}{\left|v_{NS}\right| / \left|v_{PS}\right|} \approx \frac{\left|v'_{NS}\right| - \left|v_{NS}\right|}{\left|v_{NS}\right|} = \frac{\left|Z_g + Z_{load}\right|}{\left|Z_g\right|} - 1 \tag{19}$$

To avoid the influence of grid impedance, further analysis is carried out. In specific, the short-circuit ratio (SCR) is defined as

$$SCR = \frac{V_t^2}{\left|Z_g\right| P_{rated}} \tag{20}$$

where, V_t and P_{rated} are the rated ac line to line voltage and the inverter power, respectively. Considering a DG operating at unity power factor, as the inverter power generation and the local load consumption are closely matched, the relationship between rated power and the load impedance is

$$P_{rated} = \frac{V_t^2}{R_{load}} \approx \frac{V_t^2}{\left|Z_{load}\right|} \tag{21}$$

Combing (20) and (21), the relationship between the impedance of the local load and grid can be derived as

$$\left|Z_{load}\right| = \left|Z_g\right| \cdot SCR \tag{22}$$

Assuming $R_g = n \cdot X_g$, (19) can be presented as

$$\Delta VU = \frac{\sqrt{(R_g + R_{load})^2 + X_g^2}}{\sqrt{R_g^2 + X_g^2}} - 1 = \sqrt{1 + SCR^2 + \frac{2n}{\sqrt{n^2 + 1}} \cdot SCR} - 1 \tag{23}$$

Thus, when the threshold of ΔVU is set as 0.5, this detection method can work properly under

$$\sqrt{1 + SCR^2 + \frac{2n}{\sqrt{n^2 + 1}} \cdot SCR} - 1 > 0.5 \tag{24}$$

If (24) is correct for $n > 0$, it can be derived that SCR > 1.12. When n is a known value in the practical grid, SCR value could be further reduced. In IEEE Std. 1547-2003, the grid-connected inverter is only required to operate stably under SCR > 20, and a weak grid in the HVDC system is defined as SCR < 3 in IEEE Std. 1204-1997 [34]. So, the threshold setting of ΔVU > 50% is sufficient for islanding detection under various grid conditions.

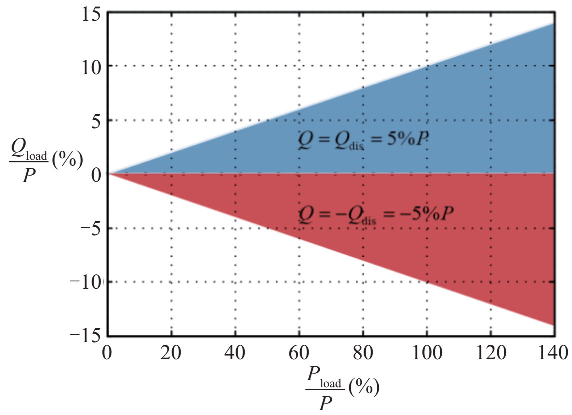

Fig. 11. Non-detection zone of BRPV with $Q_{dis} = 5\% P$.

As for the harmonic deviation, it is relevant to local load conditions. If local load is resistive load or the non-linear load is relatively large, the ΔTHD is very likely to be higher than 100% after islanding. While the capacitive load is relatively large or the local load impedance is not much higher than the grid impedance, the voltage harmonic may not be higher than the threshold. However, as the VU method is sufficient for islanding detection under various grid conditions, the THD method works as an additional method to increase detection reliability in the VU/THD method. Therefore, the threshold setting of VU/THD method in the proposed method is sufficient to pre-identify the islanding condition.

For the BRPV method, it should be able to eliminate the NDZ. When the power factor Q_f of the local load is set as 2.5 according to the requirements of IEEE Std. 929 and IEEE Std. 1547, f_{max} and f_{min} are given as 50.5 Hz and 49.5 Hz in 50 Hz system [29], (14) can be represented as

$$Q_{dis} > 5\% P \tag{25}$$

Thus, the amplitude of reactive power perturbation in the BRPV can be selected as

$$Q_{dis} = 5\% P \tag{26}$$

Fig. 11 gives the NDZ with the amplitude $Q_{dis} = 5\% P$ in BRPV, there is no overlap between two parts where the output reactive power equals Q_{dis} and $-Q_{dis}$ respectively, which means the NDZ is eliminated.

The perturbation time T_{+Q} and T_{-Q} of reactive power with positive amplitude Q_{dis} and negative amplitude $-Q_{dis}$ are selected to be equal as

$$T_{+Q} = T_{-Q} = T_Q \tag{27}$$

where, T_Q is the variation time. Considering the system transient response according to the analysis in [28], when time constant of first-order filter $\tau = 0.001$, and PI regulator parameters $K_{pPLL} = 10$, $K_{iPLL} = 2000$, the transient response time can be calculated as $t_s \approx 70.4$ ms. Thus, the perturbation time in

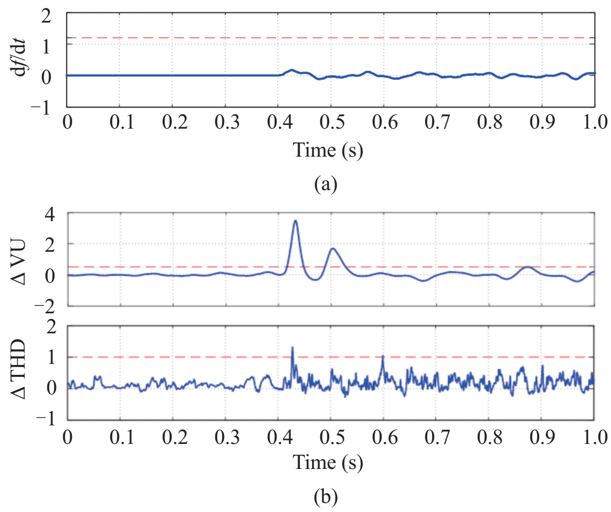

Fig. 12. Islanding detection performance of (a) ROCOF method and (b) VU/THD technique in proposed method when power is matched.

the proposed method can be set as

$$T_Q = 150 \text{ ms} \tag{28}$$

This perturbation time setting is sufficient for islanding detection in the proposed method, and the total islanding detection time is less than 300 ms which is much shorter than 2 s as required. And this setting also enhances the synchronous operation in multiple inverters system as long as the active methods in multiple inverters can be successfully triggered in 79.6 ms.

IV. Performance Comparison

To show the strengths of the proposed hybrid islanding detection method, comparative analysis between the method proposed in this paper and a typical hybrid method introduced in [23] is carried out in this section. And the comparison is based on three aspects: non-detection zone, perturbation, and detection time, which are the most important issues of the islanding detection method.

In specific, reference [23] presented a hybrid method based on the combination of ROCOF and optimized SFS, where the passive ROCOF method was initially proposed for islanding detection of synchronous generator (SG) based DG, which may fail when the power mismatch is quite small in SG-based DG [11]. In practice, the frequency is coupled with reactive power under islanding condition as illustrated in (6). The relationship between the frequency variation and reactive power mismatch can then be derived as

$$\Delta f = -\frac{\Delta Q}{12\pi C V^2} + \frac{1}{4\pi}\sqrt{\frac{\Delta Q^2}{9C^2V^4} + \frac{4}{LC}} \tag{29}$$

It can be observed that the ROCOF method will also fail in inverter-based DG when the power mismatch is small.

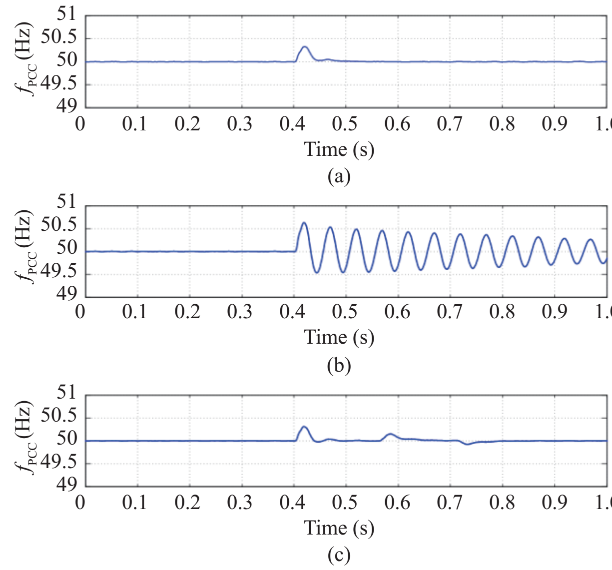

Fig. 13. Frequency response under voltage dip in a weak grid when (a) no islanding detection methods. (b) ROCOF and SFS hybrid method and (c) the proposed hybrid method are adopted.

While the VU/THD method can still work properly as it is determined by the inverter control strategy. Fig. 12(a) shows the performance of ROCOF when the output power and the power consumed by the local load are closely matched, and the islanding happens at 0.4 s. It can be seen that the frequency variation is very small, so when the threshold is set as 1.2 Hz/s according to [23], this method will fail. The performance of VU/THD method in the proposed method under the same situation is shown in Fig. 12(b), which shows that the islanding condition can be detected correctly and timely. Thus, the VU/THD method in proposed method can detect the islanding condition more precisely compared with ROCOF.

The active method adopted in [23] is the optimized SFS method, which distorts the output current by assuming the positive frequency feedback scheme, so, the output current phase is

$$\theta_{SFS} = \frac{\pi}{2}\left[cf_0 + k\left(f - f_g\right)\right] \tag{30}$$

where cf_0 is the chopping factor, k is the positive feedback gain, f is the frequency at PCC and f_g is the grid fundamental frequency. This method uses the positive feedback to increase the perturbation injected to the grid. To eliminate NDZ when $Q_f \leqslant 2.5$, k should be large enough, which increases the perturbation introduced. Thus, this method will reduce the power quality and the positive feedback will also cause system instability, and with more inverters integrated to the grid, such problem will be more serious [25], [26]. As for the BRPV method, it only has negligible impact on the power factor and will not introduce harmonic components. Although the active method will only be activated when the islanding condition is suspected by the passive method, the BRPV could have the

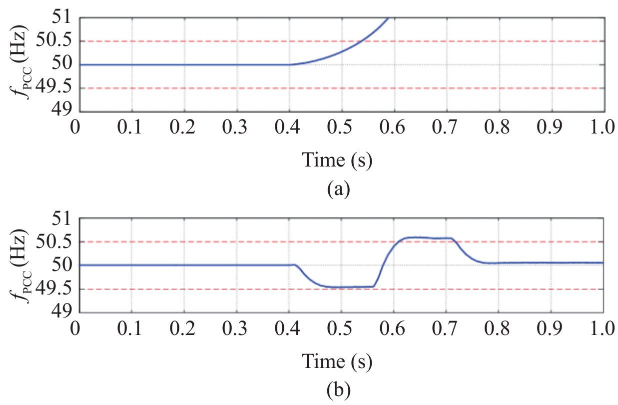

Fig. 14. Islanding frequency response of (a) ROCOF and SFS hybrid method and (b) proposed hybrid method when the resonance frequency of local load equals 50.05 Hz.

superior performance.

To show the perturbation level of these two hybrid methods, they are both tested in a weak grid system with SCR = 3. Fig. 13(a) shows the frequency variation without adopting any islanding detection methods and Fig. 13(b) and (c) show the PCC frequency variation with these two hybrid methods adopted respectively, when a 0.1 p.u. voltage dip of PCC voltage happens at 0.4 s under grid-connected mode. It can be seen from Fig. 13(b) that when the ROCOF and SFS hybrid method is adopted, the frequency will drift out of 50.5 Hz and oscillates for a long time after the voltage dip due to the positive feedback assumed. Thus, this method can cause system frequency instability, which will cause the abnormal operation of utility equipment. While as shown in Fig. 13(c), when the proposed method is adopted, the frequency is still in the permitted range. Therefore, the proposed method has a much better performance on the perturbation level.

As for the detection time, Fig. 14(a) and (b) shows the islanding frequency response of the two hybrid methods, respectively, when the resonance frequency of local load equals 50.05 Hz and islanding happens at 0.4 s. It can be seen from Fig. 14(a) that the ROCOF and SFS hybrid method can detect the islanding condition after 135 ms, and Fig. 14(b) shows the detection time of proposed hybrid method is 210 ms. It is obvious that, for the ROCOF and SFS hybrid method, the closer the resonance frequency to 50 Hz, the longer the detection time under the same system conditions outside the NDZ. Reference [23] shows that the detection time of combination of ROCOF and SFS is within 300 ms. And the proposed method can detect the islanding condition at a time interval slightly longer than 220.4 ms, since the VU/THD method can identify the islanding condition in the extremely short time and maximum BRPV variation time is about 220.4 ms after islanding according to the transient response time analysis above. Thus, both methods can detect the islanding condition in much less than 2 s in accordance with the requirements of IEEE standard 1547-2003 and GB/T 19939-2005 (China).

TABLE II
PERFORMANCE COMPARISON OF HYBRID METHODS

	ROCOF and SFS	VU/THD and BRPV
NDZ	Yes	No
Perturbation	Large and long time	Small and short time
Detection time	Meet the standard requirements	Meet the standard requirements

TABLE III
PARAMETERS OF THE SIMULATION SYSTEM

Parameter	Value
Rated output power	8 kW
DC voltage	800 V
Nominal voltage	380 V
Nominal frequency	50 Hz
Grid resistance	0.01 Ω
Grid inductance	0.3 mH
Filter inductance	3.8 mH
Load quality factor	2.5
R, L, C Parameters	R = 18.15 Ω L = 0.023109 H C = 0.000438 F

Table II further summarizes the performance of these two methods in terms of NDZ, perturbation and detection time, which demonstrates that the proposed method has a better islanding detection performance for inverter-based DGs.

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

In this subsection, the performance of the proposed hybrid method is examined under several typical conditions, including islanding, local load operation and multiple DGs system. The system depicted in Fig. 6 with the parameter values in Table III is simulated using Matlab/Simulink. The IEEE Std. 929, IEEE Std. 1547 and GB/T 19939-2005 (China) requirements are used to evaluate the effectiveness of the proposed hybrid method. It must be noted that the inverter was not shut down when the frequency is out of permitted range in cases 1 and 5 in order to clearly show the variation of the reactive power and frequency after islanding. Cases 2, 3 and 4 are carried out to verify that the proposed method will not cause nuisance trip under events that do not island the DG.

1) Islanding Detection Test

The islanding detection performance of the proposed hybrid method is evaluated under islanding condition that the quality factor and resonance frequency of the RLC load equals 2.5 and 50 Hz respectively, and the output power from the inverter and power consumed by the local load are matched, which

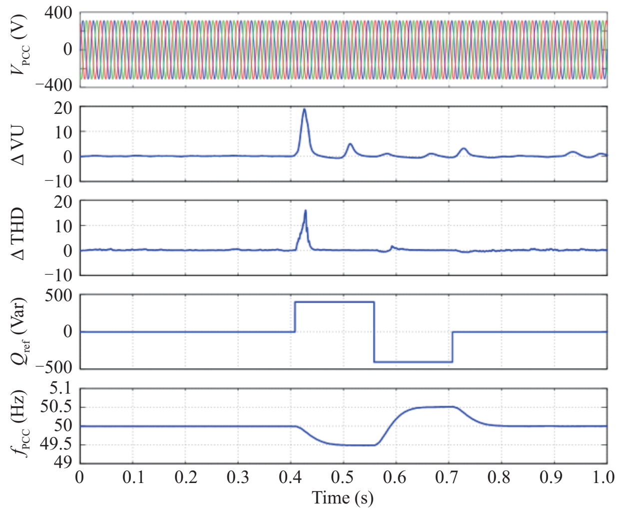

Fig. 15. Simulation results of islanding detection of the proposed method.

is the most critical condition according to the standard requirements. Simulation results are represented in Fig. 15, where the islanding happens at $t = 0.4$ s. It can be seen that the ΔVU/ΔTHD of the PCC voltage is out of the limited range immediately. Then the BRPV is activated, and the frequency reaches 49.5 Hz at $t = 0.498$ s consequently. Thus, the total detection time is 0.098 s, which is much shorter than 2 s. Therefore, the proposed hybrid method can detect the islanding condition effectively when the inverter works alone.

The performance of the hybrid method combining ROCOF method and SFS method under the same system parameters is shown in Fig. 16. Also, the islanding happens at 0.4 s. After islanding, the rate of change of frequency is much lower than the threshold 1.2 Hz/s as the resonance frequency of the load equals 50 Hz and the power mismatch is small. So, the SFS method is not activated, and the frequency of PCC voltage is maintained at 50 Hz. Thus, this method fails to detect the islanding condition. The results prove that the proposed method has better islanding detection performance than the combination of ROCOF and SFS method.

2) Large Load Switching Test

In this subsection, the proposed hybrid method is tested under the load switching condition when the DG connects to the grid. The purpose of this test is to ensure that the proposed technique will not cause nuisance trip when there is a large load switching under the grid-connected mode. This subsection only gives out the result of large three phase load switching, but it should be noted that the results in large single-phase load switching will be exactly the same. In this case, half of the local load is switched off at $t = 0.4$ s. The simulation results are demonstrated in Fig. 17. As shown in Fig. 17, although the BRPV is activated due to the sensitivity of the VU/THD technique, the frequency of the PCC voltage is maintained at 50 Hz because the DG still connects to the grid. Thus, the

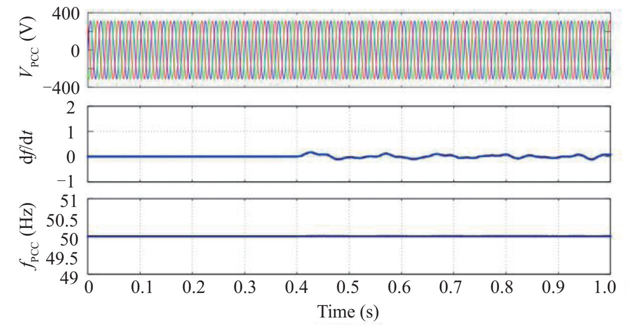

Fig. 16. Simulation results of islanding detection of ROCOF and SFS hybrid method.

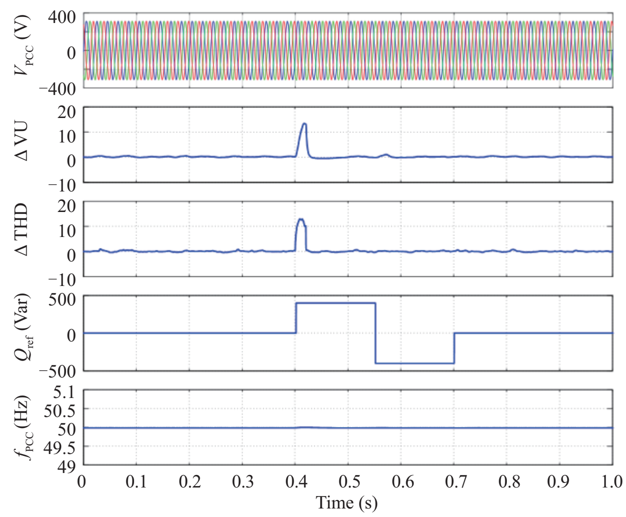

Fig. 17. Simulation results under large load switching.

proposed hybrid method will not cause nuisance trip when suffering the large load switching.

3) Nonlinear Load Integration Test

The purpose of this test is the same as the test under the large load switching. At the integration time of large local non-linear load, the harmonic content of the PCC voltage will considerably increase. In this case, a three-phase converter with rated power of 4 kW is integrated at $t = 0.4$ s. Simulation results are shown in Fig. 18. Being the same as the load switching case, ΔVU/ΔTHD exceeds the threshold and BRPV method is activated, but the frequency is also sustained by the grid. Thus, non-linear load integration will also not cause false trip when the proposed method is adopted.

4) Grid Voltage Dip Test

This subsection tests the performance of the proposed method under grid voltage dip to verify the security under gird faults that do not island the DG. As Fig. 19 shows, a 0.13 p.u. voltage dip happens at 0.4 s under grid-connected mode, and the threshold of VU/THD method is reached due to the reactive power variations, then BRPV method is activated. But as the

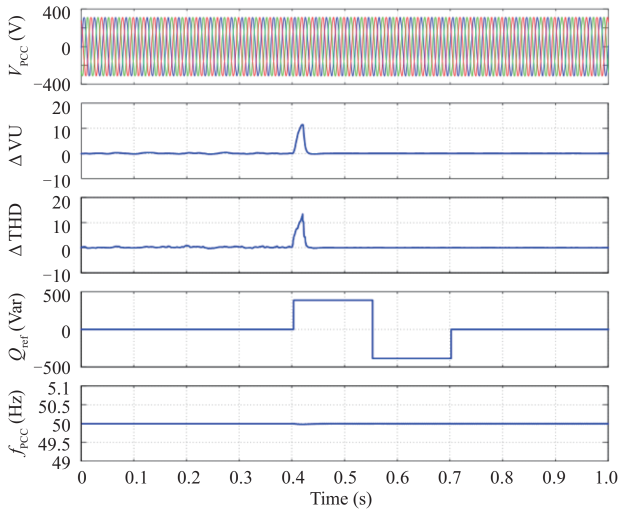

Fig. 18. Simulation results under nonlinear load integration.

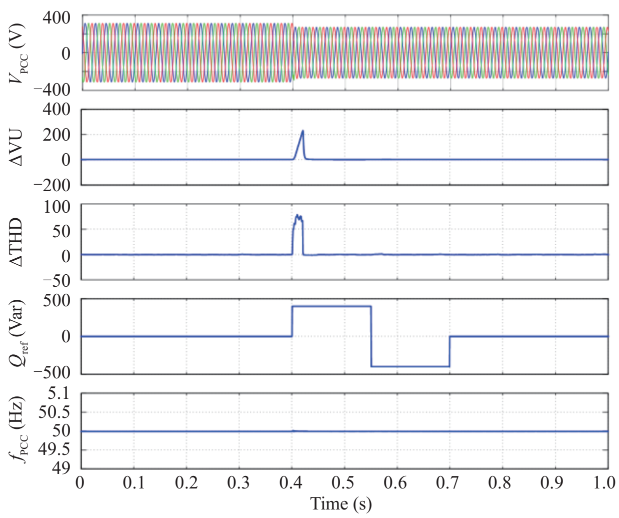

Fig. 19. Simulation results under voltage dip.

inverter still connects to the grid, the frequency remains in the permitted range. Therefore, the proposed method can guarantee the security of islanding detection under gird faults that do not island the DG.

5) Islanding Detection Test in Multiple Inverters System

A DG system consist of four parallel connected inverters is employed for multiple inverters system verification, and the power consumption of local load is 32 kW. Results are depicted in Fig. 20, where the islanding happens at $t = 0.4$ s. It is observed that after the islanding happens, the deviation exceeds the threshold of VU/THD method, and the BRPV is activated in all inverters at the same time. The frequency drifts under 49.5 Hz at $t = 0.51$ s, so the total detection time is 0.11 s, which is very close to the detection time of single inverter system. Thus, the proposed hybrid method will not cause counteraction among inverters, and can work effectively in multiple inverters system.

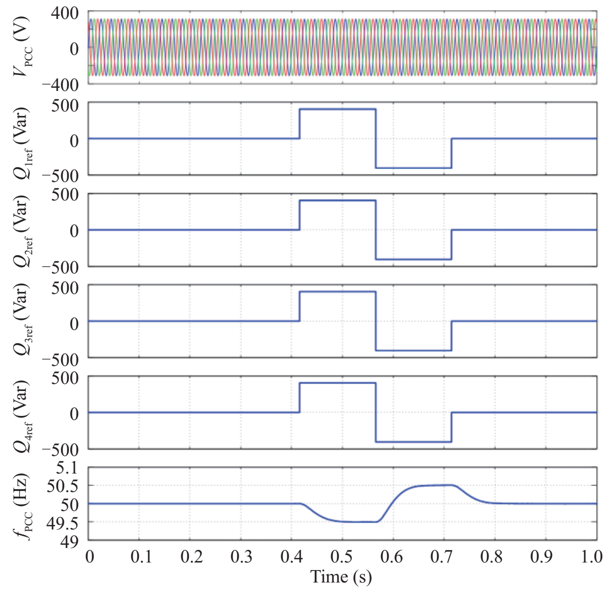

Fig. 20. Simulation results of islanding detection in parallel-connected multiple inverters system.

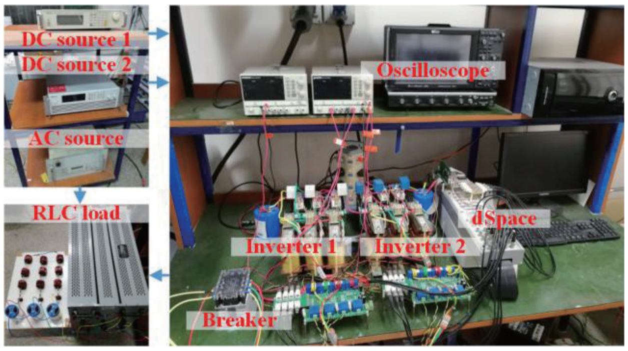

Fig. 21. Experimental platform.

B. Experimental Results

Experimental platform is shown in Fig. 21. DC sources are connected to the inverters to power the parallel RLC load, and an AC source as utility is also connected to the load. The inverter is controlled in constant power mode with output power of 1 kW which is the same as the load consumption. The grid phase voltage is set as 60 V and the frequency is 50 Hz, resonance frequency and Q_f of the RLC parallel-connected load are 50 Hz and 2.5, respectively. The breaker is used to perform the islanding event. Fig. 22 shows the waveforms of the PCC voltage and current when the inverter operates in grid-connected mode with reactive power $Q = 0$.

The experimental results of islanding detection are shown in Fig. 23. At 0.4 s, the rising step of the islanding signal means the occurrence of islanding. The islanding condition is detected by the passive method at 0.452 s, and the active method is activated at the same time. The BRPV controls the output reactive power at 5%P and −5%P, and the frequency drifts out of range successively. It is shown that the frequency

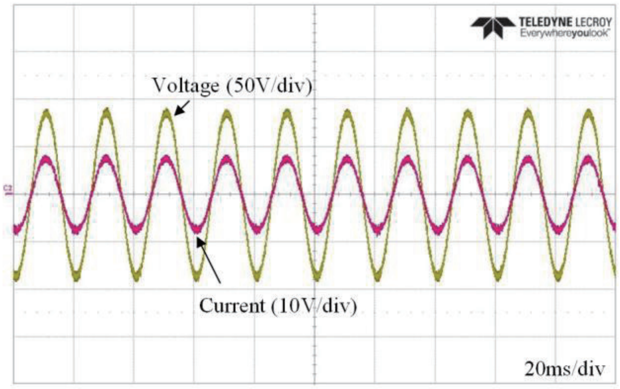

Fig. 22. Experimental waveforms under grid-connected mode.

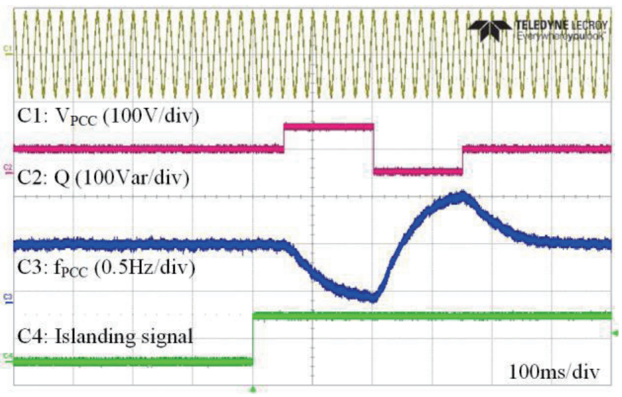

Fig. 23. Experimental results of islanding detection of the proposed method.

drifts lower than 49.5 Hz at 0.538 s, which means the islanding condition is detected. Therefore, the total detection time is 0.138 s. So, the results validated that the proposed hybrid method can detect islanding condition timely and precisely. As a comparison, the results of combined ROCOF and SFS method is shown in Fig. 24, where the frequency is almost unchanged after islanding. So, the SFS method is not activated and islanding condition cannot be detected.

Fig. 25 presents the results when half of the load was cut off. The load is cut off at 0.4 s, and the BRPV is activated as the ΔVU/ΔTHD exceeds the threshold. But the frequency is sustained by the grid, so the inverter will not trip and work normally afterwards. The results of non-linear load integration are shown in Fig. 26, and the integration time is 0.4 s. As the frequency is sustained by the grid, non-linear load integration will also not cause false trip. This proves that the proposed hybrid method will not cause nuisance trip.

Results of islanding detection in multiple inverters system is illustrated in Fig. 27, where the proposed hybrid method is tested by two parallel-connected inverters system. Islanding happens at 0.4 s, then ΔVU and ΔTHD exceed the threshold in both inverters and the BRPV is activated almost at the same time, then the frequency of PCC drifts lower than 49.5 Hz at 0.532 s. So, the total detection time is 0.132 s, which is close to the single inverter case.

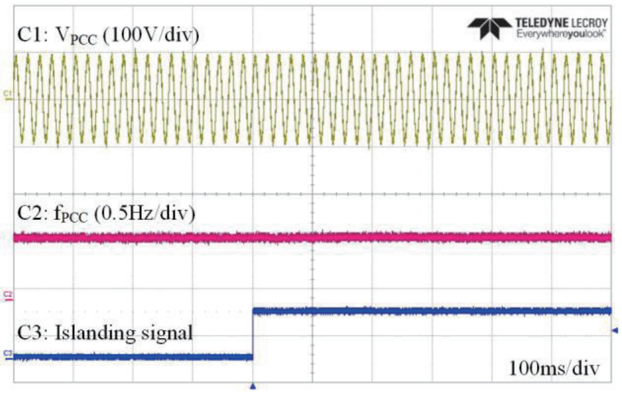

Fig. 24. Experimental results of islanding detection of ROCOF and SFS hybrid method.

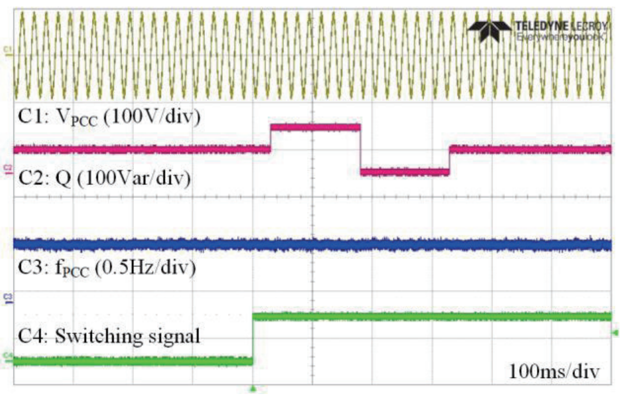

Fig. 25. Experimental results under large load switching.

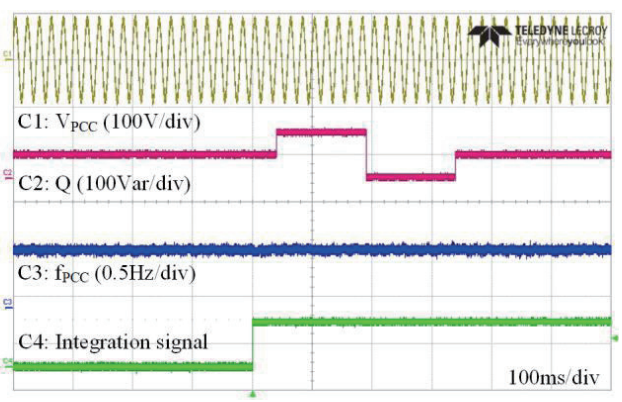

Fig. 26. Experimental results under non-linear load integration.

VI. Conclusion

This paper makes a comprehensive characteristic analysis and obtains design principles for the hybrid method in inverter-based DGs. Based on these principles, a hybrid method, which is suitable for inverter-based DG and can work properly in multiple inverters system, is proposed. The proposed method combines the VU/THD method and the BRPV method, where the BRPV method is only implemented when the islanding condition is suspected by VU/THD method. By

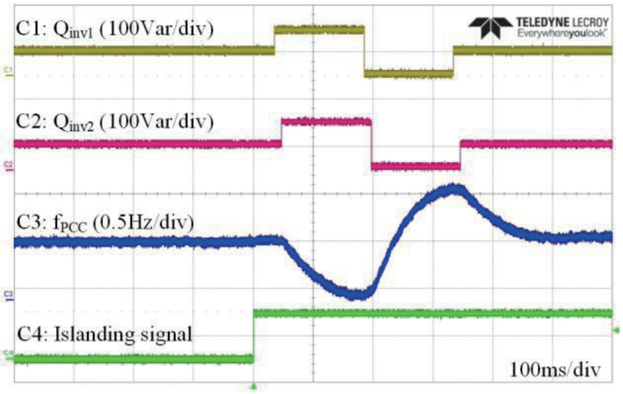

Fig. 27. Experimental results in multiple inverters system.

combining them together, the islanding detection performance can be improved significantly. It has been shown that, the proposed method can detect the islanding condition timely by properly setting parameters, with the elimination of NDZ and avoiding nuisance trip at the same time. Besides, the BRPV only perturbs the reactive power without introducing harmonics and brings the negligible effect on power factor. Comparison analysis shows that the proposed method has the more satisfactory islanding detection performance for inverter-based DGs. Simulation and experimental results under various conditions based on IEEE Std. 929 and IEEE Std. 1547 were carried out to verify the islanding detection performance of the proposed method.

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