Novel islanding detection method for inverter-based distributed generators based on adaptive reactive power control

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Abstract: Here, a novel active islanding detection method for inverter-based distributed generators (IBDGs) is presented. In order to reduce the disturbance in grid-connected mode and realise rapid and effective detection during islanding, the linear reactive power disturbance is utilised in the proposed method and its slope can change adaptively. The voltage variation and correlation factor between reactive power disturbance and frequency variation are proposed as criteria for disturbance slope adjustment. In addition, considering IBDGs located at different positions can detect the same frequency variation characteristics, the value of the frequency is used as the criteria to control the disturbance values, which can guarantee the synchronisation of disturbances added on different IBDGs without the need of communication. According to the anti-islanding test system recommended in IEEE Std.929-2000, the effectiveness of the method has been validated with several case studies in the power systems computer-aided design (PSCAD)/EMTDC environment.

1 Introduction

Using renewable energy to generate electricity, the inverter-based distributed generator (IBDG) is being widely applied to protect the environment and make the power industry development sustainable [1]. Islanding is a condition in which a portion of the utility system that contains both the IBDG and load continues operating, while this portion is electrically separated from the main utility [2]. Inadvertent islanding can lead to power quality problems, serious equipment damage, and even safety hazards to utility operation personnel [3]. Therefore, the IBDG has to detect islanding rapidly and cease to operate to prevent the damages mentioned above.

Generally, passive and active methods are the well developed and mainly used islanding detection methods. Passive methods have cost and technology neutral merits, but they may fail to detect islanding when the load power consumption closely matches the IBDG's output [4]. On the other hand, in order to reduce or even eliminate the non-detection zone (NDZ), active methods rely on intentionally injecting disturbances or harmonics into some IBDG parameters to identify whether islanding has occurred [5]. Although active methods suffer smaller NDZs, they sacrifice power quality and reliability of the power system during normal operation. Moreover, many active methods only work well when they are applied in the single IBDG scenario. In multiple-IBDG situations, these methods have difficulty in maintaining synchronisation of the intentional disturbances. Therefore, they may not work owing to the averaging effect when applied in multiple-IBDG operation [6, 7].

Islanding detection is just one necessary function for the IBDG and so the detection method should be easily implemented. Schemes based on reactive power control to detect islanding can meet this requirement with small disturbances and become much attractive. Several methods have been proposed only based on redesigning reactive power reference for the IBDG or injecting reactive power/current disturbance [8–16]. The basic mechanism of these methods is to create the reactive power mismatch, which can drive the frequency of the voltage at the point of common coupling (PCC) to change during islanding.

The proposed method here is also based on reactive power control, and it is an improved method upon the studies in [14, 15]. An islanding detection method relying on equipping the IBDG interface with a linear *Q-f* characteristic was proposed in reference [14]. The slope of the IBDG *Q-f* curve was adjusted to be steeper than that of the load *Q-f* curve. Thus, the reactive power mismatch would force the frequency of the PCC voltage to deviate outside the thresholds during islanding. However, the slope of the load *Q-f* curve was unknown in advance. Therefore, it was hard to guarantee that the slope of the IBDG *Q-f* curve, which was a preset and fixed value, would be steeper than that of the load curve. In order to eliminate the non-detection zone (NDZ) and make active and reactive power mismatches force the frequency to deviate at the same direction during islanding, the crossing point of the IBDG and load *Q-f* curves was designed to be outside the frequency thresholds according to the value of the PCC voltage in [15]. However, the PCC voltage values for IBDGs in different locations might vary a lot due to the long distance and the large power flow. Thus, it was also possible that the reactive power disturbances on different IBDGs offset each other. Moreover, reactive power disturbances were large and they became much larger especially when the frequency came near its thresholds according to above two methods. This would do harm to the power quality in grid-connected mode and the situation became worse during frequency fluctuation.

Here, the linear reactive power disturbance is utilised and its slope can change adaptively based on values of the correlation factor between the reactive power disturbance and the frequency variation, the PCC voltage and its frequency, and the preset lasting time of the disturbance. With proper and more precise design, the proposed method has following features: (1) Detect islanding rapidly with zero NDZ property; (2) Reduce the reactive power disturbance during normal operation; and (3) Guarantee the disturbance synchronisation for multiple-IBDG scenarios.

2 Basic relationship analysis for islanding

According to IEEE Std.929-2000, the recommended test system for islanding detection study is shown in Fig. 1. It consists of an IBDG, a parallel *RLC* load, and the grid represented by a source behind impedance. The operation mode of the IBDG depends on whether the circuit breaker is closed or not. The IBDG such as photovoltaic generation and wind power generation is usually configured with the maximum power point tracking controller. Since the islanding detection time is very short, the output power can be considered to be constant during the detection. Therefore,
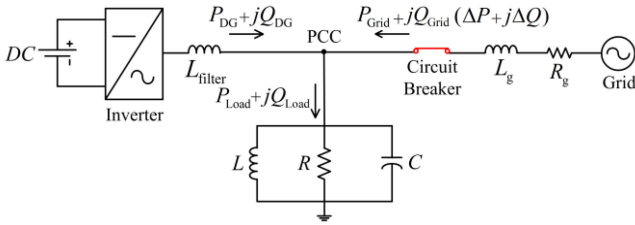
Fig. 1 *Test system for islanding detection study*

Fig. 2 *Q-f curve of a RLC load*

using a constant DC source behind a three-phase inverter, the IBDG is designed as a constant power source.

2.1 In grid-connected mode

As shown in Fig. 1, when the IBDG is connected to the utility grid, (1) and (2) describe the power flows and the active and reactive power consumed by the load:

$$P_{\text{Load}} = P_{\text{DG}} + P_{\text{Grid}} = 3\frac{V_{\text{PCC}}^2}{R} \tag{1}$$

$$Q_{\text{Load}} = Q_{\text{DG}} + Q_{\text{Grid}} = 3V_{\text{PCC}}^2\left(\frac{1}{2\pi fL} - 2\pi fC\right) \tag{2}$$

where V_{PCC} and f are the phase voltage at the PCC and its frequency, and R, L, C represent the load resistance, inductance, and capacitance, respectively. Moreover, the load's resonant frequency (f_0) and quality factor (Q_f, 2.5 is the recommended value for this parameter according to IEEEStd.929-2000) can be expressed as:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

$$Q_f = R\sqrt{\frac{C}{L}} = 2\pi f_0 RC \tag{4}$$

By combining (1), (3) and (4), (2) can be rewritten as follows:

$$Q_{\text{Load}} = P_{\text{Load}}Q_f\left(\frac{f_0}{f} - \frac{f}{f_0}\right) \tag{5}$$

For a *RLC* load whose resonant frequency is 50 Hz with the rated active power 200 kW, Fig. 2 illustrates the load *Q-f* curve. It shows the approximately linear characteristic with a negative slope for the period between 49.3 and 50.5 Hz.

2.2 In islanding mode

When the circuit breaker in Fig. 1 is open, islanding occurs. It can be inferred from (1) that if the active power mismatch ΔP ($\Delta P = P_{\text{Load}} - P_{\text{DG}} = P_{\text{Grid}}$) is not equal to zero, the PCC voltage will fall or rise no matter the IBDG operates at unity power factor or not. The amount of voltage deviation depends on the value of ΔP and their relationship can be expressed as follows [17]:

$$\Delta P = P_{\text{DG}}\left(\frac{1}{(1 + \Delta V)^2} - 1\right) \tag{6}$$

where ΔV represents the voltage deviation and it can be expressed as:

$$\Delta V = \frac{V_{\text{PCC}.i} - V_{\text{PCC}}}{V_{\text{PCC}}} \tag{7}$$

where V_{PCC} and $V_{\text{PCC}.i}$ represent the PCC voltage before and after islanding, respectively. If the active power mismatch is large enough, the passive OVP/UVP method will detect islanding according to the PCC voltage variation.
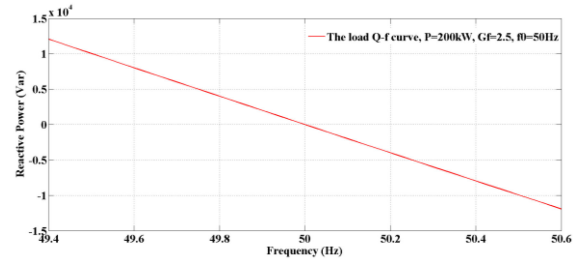
Similarly, it can be seen from (5) that the reactive power mismatch ΔQ ($\Delta Q = Q_{\text{Load}} - Q_{\text{DG}} = Q_{\text{Grid}}$) causes the frequency variation Δf ($\Delta f = f_i - f$, where f and f_i represent the frequency before and after islanding) once islanding occurs. If the IBDG operates at unity power factor, the relationship between ΔQ and Δf can be expressed as follows [17]:

$$\Delta Q = \frac{3V_{\text{PCC}}^2}{2\pi fL}\left(1 - \frac{f^2}{(f + \Delta f)^2}\right) \tag{8}$$

Thus, the frequency variation also can be used to detect islanding based on the OFP/UFP method.

According to IEEE Std.929-2000, the voltage thresholds are typically set at 88 and 110% of the rated voltage value and the normal operation range of the frequency is between 49.3 and 50.5 Hz (50 Hz is the rated frequency). Assuming that there is no active power mismatch during islanding, it can be inferred from (6) that the values of the disturbance added on the IBDG's active power reference to drive the voltage to exceed its upper and lower thresholds are at least $-17.4\%P_{\text{DG}}$ and $29.1\%P_{\text{DG}}$, respectively. On the other hand, the needed values of the reactive power disturbance to force the frequency to exceed its upper and lower thresholds are at least $-5\%P_{\text{DG}}$ and $7\%P_{\text{DG}}$, respectively, for the IBDG operating at unity power factor. It can be seen that the values of the reactive power disturbance are much less than those of the active power disturbance to force the PCC voltage or its frequency deviate outside their thresholds. Therefore, utilising the reactive power disturbance to detect islanding is a better choice.

3 Proposed islanding detection method

In order to decrease the adverse effect on power quality, the disturbance on the IBDG needs to be reduced as much as possible during normal operation. It also has to be sufficient enough to drive the frequency outside its threshold limits after islanding. Therefore, the reactive power disturbance should adjust its value adaptively to meet these two requirements.

3.1 IBDG reactive power reference

According to the studies in [15], the frequency will be forced to rise if the load reactive power consumption becomes smaller due to the positive ΔQ after islanding, whereas the frequency will drop with the negative ΔQ. Therefore, the reactive power disturbance is designed to be a linear curve with its slope adjustable to adaptively change the disturbance value for different situations. Moreover, in order to eliminate the NDZ, the reactive power disturbance should exit all the time, which means the IBDG and load *Q-f* curves are always different when the frequency is in its normal operating range.

According to the design principles above, the reactive power reference for the IBDG can be set as follows:

$$Q_{\text{ref}} = -k(f - a) + Q_{\text{ref\_rated}} \tag{9}$$

where k represents the IBDG *Q-f* slope with a changeable positive value, a is a preset value, and $Q_{\text{ref\_rated}}$ is the rated value of the reactive power reference for the IBDG.

The value of a depends on the measured value of f. If f is equal or larger than 50 Hz, the value of a will be set smaller than 50 and

the reactive power mismatch will force the frequency to increase until it exceeds the upper threshold. Otherwise, the value of a will be set larger than 50 and the frequency will finally deviate outside its lower threshold in this case. Compared with [15], this design can avoid forcing the frequency whose value is near one threshold to deviate outside the other threshold (e.g. forcing the frequency from 49.2 Hz to deviate outside the upper threshold 50.5 Hz). Thus, islanding detection can be realised more rapidly. Moreover, since IBDGs located at different positions can detect the same frequency value, the disturbances can be added on different IBDGs synchronously as well, which cannot be guaranteed in [15]. The value of a is set to be 49.9 and 50.1 for above two cases here. According to (9), the reactive power mismatch exits all the time no matter what value of f and then the NDZ can be eliminated during islanding detection.

As for the variable k, its value changes among $6\%P_{DG}$, $8\%P_{DG}$, and $10\%P_{DG}$. Basically, k is equal to $6\%\ P_{DG}$ during normal operation. Thus, when the frequency is 50 Hz in grid-connected mode, the total disturbance is only $0.6\%\ P_{DG}$, which is very small and has neglected adverse effect on power quality. On the other hand, when islanding occurs, the value of k turns to be a larger value to further shorten the detection time. According to several characteristics that indicate possible occurrence of islanding, k can adaptively change its value. For the load shown in Fig. 2, an example IBDG Q-f curve is presented in Fig. 3 with k changing adaptively at different values of the frequency (49.7, 49.9, 50.1 and 50.3 Hz). The proposed criteria used for this adaptive adjustment are introduced in the following section.

3.2 Criteria for slope adjustment

As analysed in Part 2, active and reactive power mismatches result in variations of the PCC voltage and its frequency. Thus, several characteristics can be used as criteria for adjusting the reactive power disturbance slope k to a larger value in case of possible islanding conditions.

(i) PCC voltage variation. There are always both active and reactive power mismatches between the IBDG and the local load when an islanding condition occurs. Then, the PCC voltage varies due to the active mismatch. Therefore, the PCC voltage variation can be used to adjust k. Considering that the PCC voltage can also fluctuate in grid-connected mode, the value of k changes from $6\%P_{DG}$ to $8\%P_{DG}$ only when ΔV satisfies the following constraint:

$$|\Delta V| \geq 0.04 \qquad (10)$$

In order to avoid large disturbance caused by voltage fluctuation during normal operation, if there are no other criteria are satisfied to adjust k to be larger value, the value of k will change back to be $6\%P_{DG}$ after 1 s. It should be noted that if the frequency deviates from the rated 50 Hz, the voltage root mean square calculated by the Fourier algorithm will not be accurate, which has to be modified [18].
(ii) Correlation factor between the reactive power mismatch and frequency variation. According to (9), the negative ΔQ forces the frequency to continuously drop during islanding and the positive ΔQ drives the frequency to rise. Therefore, there is a correlation between ΔQ and Δf when islanding occurs. Accordingly, the correlation factor can be used as a criteria for slope adjustment. The proposed correlation factor is defined as follows:

$$C_f = \begin{cases} -100k(f - 49.9)(50 - f), & f \geq 50\,\text{Hz} \\ -100k(f - 50.1)(50 - f), & f < 50\,\text{Hz} \end{cases} \qquad (11)$$

where C_f is the correlation factor. It is the product of an amplification factor 100, the reactive power disturbance and the frequency variation and it is a positive value during islanding. The function of the amplification factor is to make C_f large enough for accurate judgement.
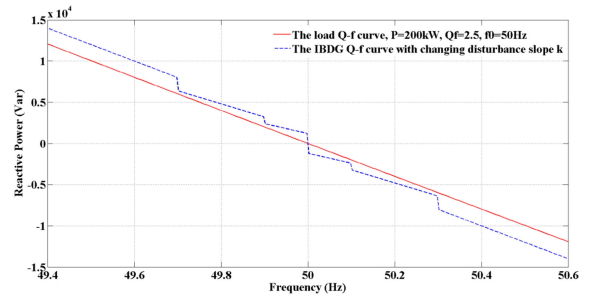

Fig. 3 *IBDG Q-f curve with adaptive k*

When C_f increases constantly and finally it is larger than $12\%\ P_{DG}$, which means the frequency is forced to continuously rise until it is larger than 50.1 Hz or drop until it is smaller than 49.9 Hz according to (11), the value of k changes from $6\%\ P_{DG}$ to $8\%P_{DG}$ or from $8\%P_{DG}$ (caused by the PCC voltage variation) to $10\%P_{DG}$. If C_f increases constantly and it is finally larger than $96\%P_{DG}$ with k equal to $8\%P_{DG}$, k will change to be $10\%P_{DG}$. Both the values of k and f change a lot in these situations. Therefore, the reactive power disturbance becomes large enough to force the frequency to deviate outside its thresholds and it can be used to detect islanding effectively combined with the passive OFP/UFP method. In addition, if the frequency is still in its normal range after k having changed its value to be a larger one for 1 s, k will change back to be $6\%P_{DG}$.

In grid-connected mode, the rated frequency is 50 Hz and accordingly C_f is 0. Thus, k remains to be $6\%\ P_{DG}$ making the disturbance neglected. If the frequency fluctuates during normal operation, C_f will rise and fall as well. The requirement of constantly increasing cannot be met and k would not change to be a larger value. Therefore, the disturbance is always neglected in grid-connected mode.

Compared with the method in [15], the proposed method here provides a finer control of the reactive power reference for the IBDG. Accordingly, the disturbance becomes much less when the frequency fluctuates in grid-connected mode. The effectiveness of the proposed method is much better. In addition, there is no need to instantaneously measure the load reactive power consumption in this method, making the method much easier to implement. The disturbance has no connection with Q_{Load} and this avoids frequent changes of the disturbance caused by load switching as well.
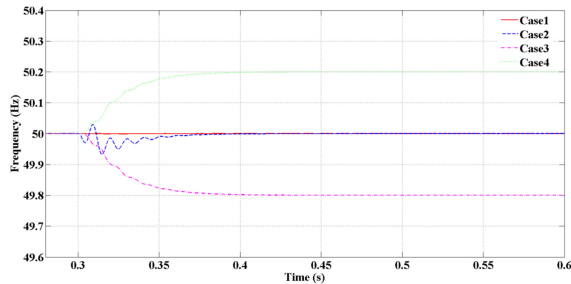
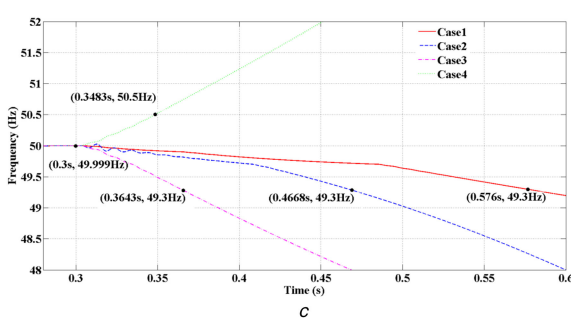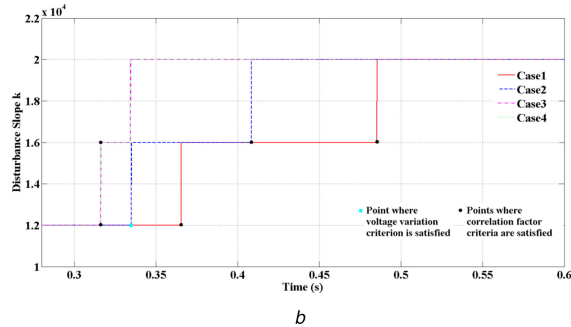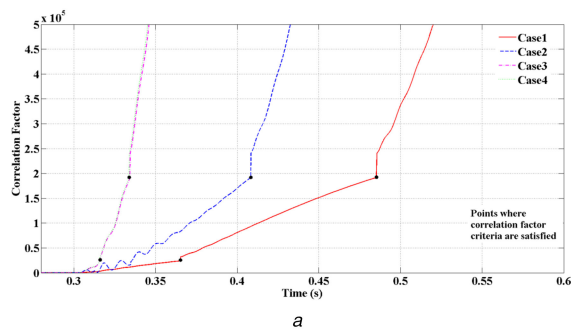## 4 Performance of the proposed method

In this section, several test cases are simulated on the power systems computer-aided design (PSCAD)/EMTDC based on the system in Fig. 1. The IBDG simulated in this section is assumed to operate at unity power factor, which means its rated reactive power reference will be 0 Var. The IBDG's active power reference is set to 200 kW and the rated phase voltage is 231 V. The value of parameter R is set at 0.8 ohm to match the IBDG's output active power and a wide variety of active power mismatch conditions can be created by changing the value of R. L and C are set at 1.0186 mH and 9947.2 µF with Q_f equal to 2.5 and f_0 equal to 50 Hz. By changing the values of L and C, different values of f_0 can be created. The RLC load with above values is supposed to be the most difficult case for islanding detection because there are no power mismatches after islanding. The islanding is initiated at $t = 0.3$ s.

As analysed in Part 3.2, C_f is the main criteria for the adjustment of k. If the PCC voltage variation caused by active power mismatch is larger than 0.04 p.u., k will adjust its value much faster, thus shortening islanding detection time. The performance of the proposed method is tested in this part. As shown in Table 1, four sets of values of parameters R, L and C are configured (Q_f is equal to 2.5 in case1, case3 and case4).

Fig. 4 illustrates frequencies without any disturbance for above four cases. It can be noted from Fig. 4 that islanding cannot be detected according to the passive OFP/UFP method.

Table 1 Load parameter setting for different test cases

Case	R, Ω	L, mH	C, µF	f_0, Hz	ΔV, V
1	0.8	1.0186	9947.2	50	0
2	0.7224	1.0186	9947.2	50	−0.05
3	0.8	1.0227	9987.1	49.8	0
4	0.8	1.0145	9907.6	50.2	0

Fig. 4 *Frequencies without any power disturbance*

Fig. 5 *Performance of the proposed method*
(a) Correlation factor, *(b)* Disturbance slope k, *(c)* PCC voltage frequency

Fig. 5 illustrates the correlation factor C_f, the disturbance slope k, and the frequency f during islanding in each test case. It can be noted from Fig. 5a that C_f is continuously increasing after islanding and the changing speed varies with different k. As shown in Fig. 5b, k adaptively changes when either the voltage variation criteria or the correlation factor criteria is satisfied. Compared with case 1, k turns to be a larger value much faster in case 2 due to the voltage variation even though C_f fluctuates and the C_f criteria is not satisfied in first 65 ms. The values of C_f and k in cases 3 and 4 changes with the fastest speed, and they are almost same in these

two cases because of the same frequency difference between f_0 and the rated 50 Hz. Therefore, it can be seen from Fig. 5c that islanding can be detected with the shortest time in cases 3 and 4 (64.3 and 48.3 ms, respectively) and the detection time in case 2 (166.8 ms) is less than that in case 1 (276 ms). In addition, there is no NDZ with the proposed method.

If the three preset values of k are set to be larger or the thresholds of the correlation factor criteria are configured with smaller values, the detection time will be further shortened. However, there is an offset between faster islanding detection and better power quality.

5 Conclusions

An active islanding detection method for the IBDG based on reactive power control is proposed here. The reactive power disturbance can adaptively change its slope based on voltage variation and correlation factor criteria. This piecewise changeable slope and the mechanism of changing back to its original value can both avoid large disturbance in grid-connected mode and realise islanding detection with zero NDZ property and fast speed as well.

6 Acknowledgments

7 References

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