A New Islanding Detection Method Based on Feature Recognition Technology

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Abstract

Three-phase grid-connected inverters are widely applied in the fields of new energy power generation, electric vehicles and so on. Islanding detection is necessary to ensure the stability and safety of such systems. In this paper, feature recognition technology is applied and a novel islanding detection method is proposed. It can identify the features of inverter systems. The theoretical values of these features are defined as codebooks. The difference between the actual value of a feature and the codebook is defined as the quantizing distortion. When islanding happens, the sum of the quantizing distortions exceeds the threshold value. Thus, islanding can be detected. The non-detection zone can be avoided by choosing reasonable features. To accelerate the speed of detection and to avoid miscalculation, an active islanding detection method based on feature recognition technology is given. Compared to the active frequency or phase drift methods, the proposed active method can reduce the distortion of grid-current when the inverter works normally. The principles of the islanding detection method based on the feature recognition technology and the improved active method are both analyzed in detail. An 18 kVA DSP-based three-phase inverter with the SVPWM control strategy has been established and tested. Simulation and experimental results verify the theoretical analysis.

Key words: Feature recognition technology, Islanding detection, Non-detection zone, Three-phase inverter system, Voltage harmonic

I. INTRODUCTION

Three-phase grid-connected inverters are an important part of distributed generation systems. An inverter may continue supplying power to a local load when it is disconnected from the grid. In this case, islanding happens and electrical equipment is damaged. As a result, personal safety can be threatened. Therefore, islanding detection is necessary to improve the stability and safety of inverter systems [1]-[6].

Passive islanding detection methods detect the amplitude, frequency, phase angle and harmonic content of the grid voltage. It is easy to realize and does not cause additional current distortion. However, the non-detection zone cannot be avoided [7]-[11]. Active islanding detection methods can reduce the non-detection zones. However, disturbances such as frequency or phase drifts of the grid current are added. The quality of the grid current can be reduced because of these disturbances [12]-[15].

Changes in the parameters of an inverter system can reflect its working condition. If the inverter is disconnected from the grid, some of the parameters may change and can be easily detected. These parameters can be seen as the "features" of the inverter system. The working condition of the system can be recognized depending on these features. Islanding can be detected when these features are changed. As a result, modern feature recognition technology can be introduced to realize islanding detection. Feature recognition contains speaker recognition, image recognition and so on [16]-[20]. Speaker recognition is a typical feature recognition technology. It provides a way to take advantage of speaker features regardless of verbal information [21]. However, it cannot be directly applied to islanding detection. In the Vector Quantization (VQ)-based feature recognition, the decision is made by measuring the similarities between a testing pattern and every codeword achieved during training [22]-[27]. In a three-phase inverter system, the codeword can be seen as the parameters of
the system, such as the three-phase current and voltage, the DC voltage, the grid frequency, and so on. The codebook is the vector formed by different codewords. A codebook is a collection of codewords which can reflect a certain feature. It can be seen as a feature vector and can be obtained by a theoretical analysis of the inverter’s operation condition instead of the training of signals. The codebooks can form an operation vector model of the inverter system. With this model, changes in the features in an inverter system can be detected in real-time.

For the above reasons, a novel islanding detection method based on modern feature recognition technology is proposed in this paper. The features of an inverter system are analyzed. When islanding occurs, one or some of the features change. Abnormal phenomenon can be detected and the non-detection zone can be eliminated. To exacerbate the changes of the features and accelerate the speed of detection, an active islanding detection method is applied. This can help avoid miscalculations. When the grid-connected inverter operates normally, the quality of the grid current is not reduced. When the inverter is disconnected from the grid, the changes in the features can be exacerbated. The operating condition of the inverter will be analyzed in Section II. The vector model will be established and an islanding detection method based on modern feature recognition technology will be introduced in Section III. An active islanding detection method will be described in Section IV. Simulation and experimental results obtained from an 18kVA three-phase grid-connected inverter will be presented to verify the theoretical analysis in Section V.

II. OPERATION ANALYSIS

A. Parameters in the Inverter System

Fig. 1 (a) shows a control diagram of a three-phase grid-connected inverter system. There are several parameters in this system. \( i_a, i_b, \) and \( i_c \) are the AC side current. \( u_a, u_b, \) and \( u_c \) are the AC side voltage. \( e_a, e_b, \) and \( e_c \) are the grid voltage. When the inverter works in the grid-connected condition, \( u_a, u_b, \) and \( u_c \) are the same as \( e_a, e_b, \) and \( e_c, \theta \) is the phase angle of the grid voltage, which can be obtained by a PLL. \( i_a, i_b, \) and \( i_c \) are the active and reactive current. \( i_a^*, i_b^*, \) and \( i_c^* \) are the references of active and reactive current.

The relationships among the parameters is shown in Fig. 1 (b). When the inverter works in the grid-connected condition, the phase angle of the AC side current is the same as that of the AC side voltage. With the PLL method, a non-ideal grid cannot influence the accuracy of \( \theta \) [28]-[31]. Therefore, \( \theta \) can be seen as the ideal value. If \( u_a, u_b, \) and \( u_c \) are sampled, the theoretical values of the AC side current \( i_a^*, i_b^*, \) and \( i_c^* \) and the projection of the three-phase voltage on the dq frame \( u_d \) and \( u_q \) can be calculated. \( i_d^* \) and \( i_q^* \) are also the theoretical values of active and reactive current. The actual value of the active and reactive current \( i_d \) and \( i_q \) can be calculated by \( i_a, i_b, \) and \( i_c, \)

The frequency of the grid \( f_1 \) can be obtained by a change in the rate of \( \theta \).

There are three situations in terms of local loads [32]-[33]. Fig. 2 shows changes in the key parameters before and after the inverter is disconnected from the grid at time \( t_0 \). The waveforms from top to bottom are for \( u_a, i_a, \) and \( \theta \). Due to the filter \( L \), the AC side current \( i_a, i_b, \) and \( i_c \) does not have sudden changes. The instantaneous changes at \( t_0 \) are not obvious because of the parallel RLC resonant load.

In Fig. 2(a), the local load is capacitive or inductive. Before \( t_0 \), the phases of \( u_a, i_a, \) and \( \theta \) are the same. \( \theta \) changes from
\(-\pi \) to \(\pi\) linearly. After \(t_0\), the phases of \(u_a\) and \(i_a\) are different. \(\theta\) reaches \(\pi\) at \(t_4\) instead of \(t_3\).

In Fig. 2(b), the local load is resistive and the powers of the load and the inverter are not matched. If the power of the load is lower than that of the inverter, the power of the inverter is partly supply to the grid. If the power of the load is higher than that of the inverter, the power of the load is partly absorbed from the grid. After \(t_0\), the phases of \(u_i\) and \(i_i\) are still the same. Thus, \(\theta\) can reach \(\pi\) at \(t_3\). When the inverter is still connected to the grid, the change of \(\theta\) is the same. However, the amplitude of \(u_a\), \(u_b\) and \(u_c\) changes, which reflects the change of \(u_e\).

In Fig. 2(c), the local load is resistive and the powers of the load and the inverter are matched. If only the fundamental components are considered, none of the parameters change after \(t_0\). In this condition, a non-detection zone may occur. To avoid this non-detection zone, at least one varying parameter needs to be determined. Therefore, further analysis is necessary.

### B. Changes in the Parameters

To avoid a non-detection zone, only the third situation is under consideration. When the inverter is connected to the grid, \(u_d\) is regulated according to standards. It is limited in a certain range. The voltage harmonics are also regulated according to standards and their content is slight. After the inverter is disconnected from the grid, \(u_a\), \(u_b\) and \(u_c\) are not clamped by the grid voltage. The harmonics of \(u_a\), \(u_b\) and \(u_c\) increase because of the switching and nonlinear load.

The voltage harmonics introduced by the switching are caused by two reasons [34]. One is dead-time. The other is caused by the SVPWM. The switching frequency current harmonic is the sector number. At a low frequency, \(m\) is 0, and \(n\) is a multiple of 3.

![Fig. 3. Voltage harmonics of the bridge leg caused by SVPWM.](image)

The voltage harmonic projections in the dq-frame can be expressed as:

\[
\begin{bmatrix}
\cos(\alpha t) \\
\sin(\alpha t)
\end{bmatrix}
= \frac{2}{\sqrt{3}} \begin{bmatrix}
\cos(\alpha t + \frac{2\pi}{3}) \\
-\sin(\alpha t + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
u_{d0} \\
u_{dA}
\end{bmatrix}
\]

(8)

Fig. 4 shows the changes in the AC side voltage caused by the SVPWM. The inverter is disconnected from the grid at the time \(t_0\). The switching frequency current harmonic is added to the ideal fundamental current of the AC side.
order to amplify the voltage harmonic, three-phase current harmonic is the switching frequency in this paper. Thus, the non-detection zone can be solved through testing the features of the inverter system can be extracted. Therefore, a HPF is applied instead of other filters. HPF is much shorter than that of a LPF (Low Passed Filter). With both low and high frequencies increase, the delay of the inverter is disconnected from the grid, the voltage harmonics contain the low and high frequency components [35]. After the voltage harmonics introduced by the nonlinear load also change. In Fig. 5, \( y_1 \) is a feature of the current in an inverter system, and \( y_2 \) is a feature of the voltage. \( u_{dh} \) is a sinusoidal variation and cannot be applied in the feature recognition as a codeword. It can be replaced by a function \( f(u_{dh}) \), which is the amplitude of \( u_{dh} \). The algorithm of \( f(u_{dh}) \) is shown in Fig. 5.

In Fig. 5, \( f_s \) is the testing frequency of \( u_{dh} \). The calculation of \( f(u_{dh}) \) costs half of a switching cycle, which is a very short time.

III. MODEL ISLANDING DETECTION METHOD

A. Establishment of a Vector Model

Changes in the parameters are analyzed in Section II. Thus, the features of the inverter system can be extracted. The feature vector can be expressed as:

\[
Y = \{ y_1, y_2 \}
\]

(6)

where \( y_1 \) and \( y_2 \) are two groups of three-dimensional vectors. They can be expressed as:

\[
y_1 = [i_a, i_b, i_c]^T
\]

(7)

\[
y_2 = [f_s, u_d, f(u_{dh})]^T
\]

(8)

\( y_1 \) is a feature of the current in an inverter system, and \( y_2 \) is a feature of the voltage. \( u_{dh} \) is a sinusoidal variation and cannot be applied in the feature recognition as a codeword. It can be replaced by a function \( f(u_{dh}) \), which is the amplitude of \( u_{dh} \). The algorithm of \( f(u_{dh}) \) is shown in Fig. 5.

In Fig. 5, \( f_s \) is the testing frequency of \( u_{dh} \). The calculation of \( f(u_{dh}) \) costs half of a switching cycle, which is a very short time.

The threshold \( \delta \) should be set reasonably set. When the inverter works normally, \( \delta \) should be larger than \( d \). When the

The cut-off frequency of the HPF should be less than \( f_s \). It is set as 2.5kHz in this paper. The voltage harmonic noticeably changes after \( t_0 \). Thus, the non-detection zone can be solved through testing \( u_{dh} \) by a HPF.

The voltage harmonics introduced by the nonlinear load also contain the low and high frequency components [35]. After the inverter is disconnected from the grid, the voltage harmonics with both low and high frequencies increase. The delay of the HPF is much shorter than that of a LPF (Low Passed Filter). Therefore, a HPF is applied instead of other filters.

The top waveforms \( u_a, u_b \) and \( u_c \) do not noticeably change after \( t_0 \). \( u_d \) and \( u_q \) are the projections of \( u_a, u_b \) and \( u_c \) in the dq-frame. The phase angle, which takes part in the coordinate transformation, is the output of the PLL. The input of the PLL is \( u_a, u_b \) and \( u_c \) so that \( u_q \) is always \( 0 \). The frequency of the three-phase current harmonic is the switching frequency \( f_s \). The bottom waveform \( Kf(u_{dh}) \) is the output of a high passed filter (HPF). The input of the HPF is \( u_d \), \( K \) is the gain of the HPF. In order to amplify the voltage harmonic, \( K \) is set as 10 in this paper. \( h \) is the voltage harmonic order, which is \( f_s / f_1 \). The cut-off frequency of the HPF should be less than \( f_s \). It is set as 2.5kHz in this paper. The voltage harmonic noticeably changes after \( t_0 \). Thus, the non-detection zone can be solved through testing \( u_{dh} \) by a HPF.

The theoretical value of the feature vector can be expressed as:

\[
C_1 = [i_a^*, i_b^*, i_c^*]^T
\]

(9)

\[
C_2 = [f_{1^*}, u_d^*, f(u_{dh}^*)]^T
\]

(10)

where \( C_1 \) and \( C_2 \) are the codebooks. \( i_a^*, i_b^*, i_c^*, f_{1^*}, u_d^* \) and \( f(u_{dh}^*) \) are the codewords. \( f(u_{dh}^*) \) is 0 in the ideal condition.

According to standard GB12325-90, the ideal value of \( f_1^* \) is 50Hz, and \( u_d^* \) is 280V. A slight deviation is allowed in the standard. Therefore, \( C_1 \) and \( C_2 \) are different from \( y_1 \) and \( y_2 \) even when the inverter works normally. Therefore, islanding should be judged by the mean square quantization distortion, which can be expressed as:

\[
d = \sum_{j=1}^{2} d_j = \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{ij} (y_{ij} - C_{ij})^2
\]

(11)

Fig. 4. Changes of the AC side voltage caused by SVPWM.

Fig. 5. The algorithm of \( f(u_{dh}) \).

Fig. 6. Comparison of the processes of the speaker recognition and the islanding detection method. (a) The speaker recognition. (b) The islanding detection method.
According to the above analysis, after the inverter is applied to exacerbate the changes in the features, miscalculation, an active islanding detection method should be used. To accelerate the speed of detection and to avoid being slight. If a disturbance is added to exacerbate the changes in the grid, the voltage is not clamped by the grid and connects to the grid. If islanding happens, the AC side voltage and current change obviously after the inverter is disconnected from the grid, because of the positive feedback, the amplitude of the current harmonic is able to increase after the inverter is disconnected from the grid, and islanding can be easily detected. According to the current loop shown in Fig. 8, \( u_{\text{dh}} \) is the output of the HPF, which was designed in section II. It is the sum of the high frequency voltage harmonics. Their frequencies are higher than the cut-off frequency of the HPF.

In a non-ideal grid, the grid harmonics are mainly the 3rd, 5th, 7th, 11th and 13th time voltage harmonics [36]. The containing of the switching frequency voltage harmonics is very slight. Therefore, \( f(u_{\text{ab}}) \) is close to 0 when the inverter connects to the grid. If islanding happens, the AC side voltage is not clamped by the grid and \( f(u_{\text{ab}}) \) increases. According to the current loop shown in Fig. 8, \( u_{\text{ab}} \) increases with an increment of \( f(u_{\text{ab}}) \). According to (7) and (8), \( f(u_{\text{ab}}) \) increases further. After a few times’ accumulation, the islanding can be quickly detected.

### IV. ACTIVE DETECTION METHOD

If an inverter is connected to a non-ideal grid, voltage harmonics always occur and \( u_{\text{ab}} \) in Fig. 5 is not zero before \( t_0 \). Islanding may be misjudged through testing \( f(u_{\text{ab}}) \) if the threshold \( \delta \) is too small. However, the changes in the features may be slight. If \( \delta \) is too high, islanding may not be detected in time. To accelerate the speed of detection and to avoid miscalculation, an active islanding detection method should be applied to exacerbate the changes in the features. According to the above analysis, after the inverter is disconnected from the grid, \( u_{\text{ab}} \) cannot be clamped by the grid. If a disturbance is added to exacerbate the changes in \( u_{\text{ab}} \), islanding can be easily detected. Fig. 7 shows an active islanding detection method.

\[
\delta = \sum_{i=1}^{3} \sum_{j=1}^{1} \alpha_{ij} (C_{ij_{\text{max}}} - C_{ij_{\text{min}}})^2 \tag{12}
\]

where \( C_{ij_{\text{max}}} \) and \( C_{ij_{\text{min}}} \) are the upper and lower limits of the codewords regulated by standards. Tab. 1 shows the processes of the speaker recognition and the proposed islanding detection method. It can be seen that the codebooks of the speaker recognition and the proposed islanding detection method can be directly obtained by the feature analysis, while the codebooks of the speaker recognition are obtained by Vector Quantization.

### V. SIMULATION AND EXPERIMENTAL RESULTS

An 18kVA three-phase grid-connected inverter with the SVPWM control method has been simulated by the simulation software MATLAB/Simulink. The grid is 220V/380V/50Hz, and the DC voltage is 700V.

Fig. 9 shows the changes in the parameters both with and without the active islanding detection method. The three-phase inverter is simulated by a three-phase current source. The amplitude of the fundamental current is 40A. The amplitude of the switching frequency positive sequence current harmonic is 1A. The switching frequency \( f_s \) is 5kHz. The RLC resonant load is 7Ω, 10.1424mH and 1000μF. The resonant frequency of the local load is 50Hz. The parameters of the HPF are the same as those from the theoretical analysis.

The inverter is disconnected from the grid at time \( t_0 \). Fig. 9 (a) shows the AC side voltage and current without the active islanding detection method. The AC side voltage and current change obviously after the inverter is disconnected from the grid, because of the positive feedback, the amplitude of the current harmonic is able to increase after the inverter is disconnected from the grid, and islanding can be detected. Thus, the islanding can be quickly detected.

Fig. 9 (b) shows the changes in the parameters both with and without the active islanding detection method. The parameters discussed in Section III change obviously after \( t_0 \). In Fig. 9 (b), the waveforms from top to bottom respectively are \( u_{\text{ab}}, u_{\text{bd}} \) and \( f(u_{\text{ab}}) \). Positive sequence current harmonics are added so that \( h = f_s/2 + 1 \) in this figure. According to \( f(u_{\text{ab}}) \), islanding can be detected. Fig. 9 (c) shows the AC side voltage and current with the active islanding detection method. The AC side voltage and current change obviously after the inverter is disconnected from the grid. Because of the positive feedback, the amplitude of the current harmonic is able to increase after \( t_0 \), which is shown in Fig. 9 (d). Thus, the islanding can be quickly detected.

Tab. 1 shows the values of the parameters of (12). The principle of the weighting factors \( \alpha_{ij} \) is that the influence of the parameters can realize an average distribution. According to Tab. 1, the threshold \( \delta \) can be set as 1.

Fig. 10 shows the passive and active islanding detection results in a non-ideal grid. An 18kVA three-phase inverter model is applied. The waveforms from top to bottom are the AC side voltage \( u_x, u_y \) and \( u_z \), the AC side current \( i_x, i_y \) and \( i_z \), the driving enable signal, \( d \) and \( \delta \). The inverter is disconnected from the grid at the time \( t=r=0.04s \).
Fig. 9. Changes of the parameters. (a) AC side voltage and current without active islanding detection method. (b) The feature parameters without active islanding detection method. (c) AC side voltage and current with active islanding detection method. (d) The feature parameters with active islanding detection method.

| TABLE I |
|---------|
| **THE VALUES OF THE PARAMETERS** |
| $i$ | $j$ | $\alpha_{ij}$ | $C_{\text{imax}}$ | $C_{\text{imin}}$ |
|---|---|---|---|---|
| 1 | 1 | 0.03 | 30 | 24.5 |
| 1 | 2 | 0.03 | 30 | 24.5 |
| 1 | 3 | 0.03 | 30 | 24.5 |
| 2 | 1 | 0.17 | 50.5 | 49.5 |
| 2 | 2 | 0.0015 | 336 | 224 |
| 2 | 3 | 0.6 | 0.28 | 0 |

Fig. 10. The islanding detection result in the non-ideal grid. (a) Passive islanding detection method ($\delta=1$). (b) Active islanding detection method ($\delta=1$). (c) Passive islanding detection method ($\delta=2$). (d) Active islanding detection method ($\delta=2$).
Fig. 11. Experimental results in the non-ideal grid. (a) Passive islanding detection method ($\delta=1$). (b) Active islanding detection method ($\delta=1$). (c) Passive islanding detection method ($\delta=2$). (d) Active islanding detection method ($\delta=2$). (e) AFD islanding detection method.

Fig. 10(a) and (b) show the passive and active islanding detection results when the threshold $\delta$ is 1. The islanding is more quickly detected with the active islanding detection method. However, sometimes $d$ is close to $\delta$ when the inverter works normally. $\delta$ should be high enough to avoid misprotection. However, it cannot be too high to detect the islanding. Fig. 10(c) and (d) show the detection results when $\delta$ is 2. The islanding may not be detected with the passive islanding detection method while the active islanding detection method can solve the problem.

An 18kVA three-phase grid-connected inverter with the SVPWM control strategy based on a TMS320F240PQA has been built to verify the analysis. The parameters are the same as those used in the simulation.

Fig. 11(a) and (b) show the experimental results with the passive and active islanding detection method when $\delta$ is 1. The waveforms from top to the bottom are the AC side voltage $u_a$, $u_b$, and $u_c$ and the AC side current $i_a$, $i_b$, and $i_c$. The islanding can be quickly detected with both methods.

Fig. 11(c) and (d) show the experimental results when $\delta$ is 2. The islanding can be quickly detected with the active method. However, the passive method cannot detect the islanding in time. Fig. 11(e) shows the experimental results with the active frequency drift (AFD) method. The detection speed of the proposed active detection method is quicker than that of the AFD method.

Fig. 12 shows the current harmonics of the grid current when the inverter works normally. There are third-time current harmonics because the three-phase transformer is not completely symmetrical. Fig. 12 (a) and (b) are the current harmonics with the passive and active islanding detection methods. Their THDs are 3.7 and 4.0, respectively. It can be seen that the active islanding detection method does not introduce a lot of harmonic. The lower $h$ is, the higher the increment of the current harmonic becomes. Fig. 12 (c) shows the current harmonics with the AFD. The THD is 4.9 and it is higher than that of the proposed method.
VI. CONCLUSION

This paper proposes a novel islanding detection method based on the modern feature recognition technology. The proposed method can identify the features of the inverter system and can calculate the quantizing distortion. The principle of the feature recognition technology is described in detail. Passive and active islanding detection methods based on feature recognition technology are analyzed. Simulation and experimental results from an 18 kVA grid-connected inverter are presented to verify the theoretical analysis. The proposed method has the following advantages:

1) This method can avoid the non-detection zone through changes of the parameters.

2) The active method can accelerate the speed of detection and avoid miscalculation.

3) Compared to the active frequency or phase drift methods, the AC side current with the proposed method has less distortion when the inverter works normally.

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