一种用於單相光伏並網發電系統的高頻孤島檢測方法

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摘 要

孤島檢測在光伏發電系統中是必有的特性。目前孤島檢測的方法有兩種：被動式孤島檢測和主動式孤島檢測。主動式孤島檢測方法需要改變系統給定的參數，這些參數往往影響了並網電流的波形和品質。本文提出了一種新的可用於單相光伏並網發電系統的主動式孤島檢測方法。首先，分析了單相並網逆變器的輸出電壓的頻譜，從而證明瞭注入高頻電流實現孤島檢測的合理性。其次，給出電網的等效模型並且研究了 PCC 節點處輸出電壓的頻率特性。然後提出將 1kHz 的擾動量注入到並網電流中並給出由變相器和變頻器組成的孤島檢測框圖。由實驗結果可知。較低頻的注入方法而言，高頻分量注入的方法既達到了孤島檢測的目標又將並網電流的諧波失真降至最低。所以該方法有著良好的工業應用前景。

關鍵詞：單相並網逆變器，孤島檢測，主動式，高頻注入。

A HIGH FREQUENCY ISLAND DETECTION APPROACH APPLIED IN SINGLE-PHASE GRID-CONNECTED PV GENERATION SYSTEM

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ABSTRACT

Island detection is a necessary feature of the photovoltaic (PV) generation system. Both passive and active anti-island methods exist. Typically, active methods modify a given parameter, which also affect the shape and quality of the injected current. A new active anti-island approach is proposed in this paper, which is suitable for single-phase grid-connected PV system. First, the output voltage of grid-connected inverter spectrum is investigated to prove feasibility. Second, the equivalent model of grid is proposed, and the
frequency response of the voltage of PCC point is also investigated. Then, 1kHz perturbation component current is selected to be injected into the grid current and the diagram of island detection method is also proposed, which mainly consists of a phase detector and magnitude detector. From the experimental results, compared to the low frequency injection, it can be seen that the proposed high frequency injection achieves the goal of anti-island detection and reduce the current distortion to the minimum as well. As a result, this technique has good industrial application prospect.

I. INTRODUCTION

The power circuit of the PV inverter system is illustrated in Fig. 1, which consists of a solar panel string and a DC link capacitor $C_{DC}$ on the DC side with an output AC filter (LC), a local parallel RLC load, an isolation transformer and the grid connected on the AC side through the utility’s breaker circuit.

When the grid is disconnected, the grid-connected inverter should stop operating. But it may still continue to operate with local loads in the case, called island state [1-2]. Thus the PV generation system should detect the island and cease to energize the area within two seconds of the formation of an island. Island can be intentional and unintentional, but in most cases, island is unintentional. In this paper, the unintentional island is considered. Although the probability of island occurrence is extremely low, an effective anti-island method is incorporated into the operation of the inverter.

There are numerous island detection methods [3-9] for grid-connected PV systems reported in the technical literature, and their development has been summarized in a number of recent technical papers and reports. They can be classified into two broad categories, passive and active methods.

The passive methods are based on the detection of the following: over-voltage/under-voltage protection (OVP/UVP), over-frequency/under-frequency protection (OFP/UFP), voltage phase jump, voltage harmonic monitoring and current harmonic monitoring. However, passive methods have a number of weaknesses and inability to detect island.

Active methods [10-18] have been developed in order to overcome the limitations of the passive methods. The active methods generate a disturbance to force a change of a power system parameter that can be detectable by the passive methods. One of the commonly-used active method is harmonic injection (HI). Harmonic injection is based on injection of harmonic current and extraction of the resultant voltage harmonic, which is dependent on the grid impedance at that frequency. It’s assumed that these frequencies are normally not present in the grid voltage so that the voltage detected at the frequency will be only the voltage drop of the grid impedance.

Usually, injection frequencies (40 Hz, 60 Hz or 75 Hz for a 50 Hz grid) are used, and linear extrapolation is used to estimate the grid impedance at these frequencies. A further development of this method is reported in references [19-22], where higher frequencies (100-300 Hz) and zero-crossing synchronization of harmonic injection are used to cause less grid disturbance, as shown in Fig. 2 [20]. It can be seen that some disturbances of the grid current still exist.

A new active anti-island approach is proposed in this paper which is suitable for single-phase grid-connected PV system. First, the output voltage of grid-connected inverter spectrum is investigated to prove it is feasible to
inject current component at high frequency. Second, the equivalent model of grid is proposed. Based on the model of the grid, the magnitude and phase frequency response of the output voltage across the point of common coupling are obtained. After distinguishing between the frequency response of the output voltage in the island state and in the grid connected state, it is found that it’s wise to inject perturbation current whose frequency is in range of 200 kHz-3 kHz to detect whether the PV generation system is in island state or not. In this paper, 1 kHz perturbation current is injected. Then, the diagram of island detection method is proposed, which mainly consists of phase detector and magnitude detector. All of the diagrams are developed using DSP (TMS320F28335), and the structure of key element PLL is also mentioned in this paper. Finally, the experimental results prove the feasibility and high-performance of proposed method.

**II. OUTPUT VOLTAGE OF GRID-CONNECTED INVERTER SPECTRUM**

![Fig. 3 Typical waveform of single-phase grid-connected inverter for the unipolar SPWM: (a) carrier and modulating signals; (b) output voltage; (c) output voltage spectrum](image)

**Fig. 3** Typical waveform of single-phase grid-connected inverter for the unipolar SPWM: (a) carrier and modulating signals; (b) output voltage; (c) output voltage spectrum

Fig. 3 shows the typical waveforms of single-phase grid-connected inverter.

The output voltage is given by

\[
v_o(t) = V_o M \cos(o_f t)
\]

\[
+ \frac{4V_o}{\pi} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{1}{2m} J_n(m \pi M) \cos[m \pi f_c t - (2n - 1) \omega_f t]
\]

where \(V_o\) is the input DC voltage, \(\omega_f\) is grid frequency, \(\omega_c\) is switching frequency, \(M\) is the amplitude modulation index, defined by:

\[
M = \frac{V_{control\ peak}}{V_{tri\ peak}} \quad 0 < M < 1
\]

and \(J_n(x)\) is Bessel function.

The first term of Equation (1) is the fundamental component of output voltage given by

\[
v_{o1}(t) = V_o M \cos(o_f t)
\]

If \(m_f\) equal to \(\frac{o_f}{o_c}\), is even, the harmonics in the output voltage appear at normalized odd frequencies centered around twice the normalized carrier frequency \(m_f\) and its multiples. Specifically, \(h = lm_f \pm k, l = 2, 4, 6, \ldots\), where \(k = 1, 3, 5,\ldots\)

In practice, \(m_f\) is selected who is equal to 200, and \(M\) is equal to 0.9. Thus, the theoretical output voltage harmonics are shown in Fig. 4. It can be seen in Fig. 4 that only fundamental component can be found at low frequency. Thus, if a small amount of high frequency (1
kHz) current is injected into grid, the perturbation component at high frequency (1 kHz) will exist in the output voltage. If the frequency of injected current is close to the grid frequency, it is hard to distinguish between perturbation component and fundamental component. However, if the frequency of injected current is far from the grid frequency, it would be difficult to detect the perturbation component. In this paper, the injected current is selected whose frequency is 1 kHz.

III. THE EQUIVALENT CIRCUIT OF GRID AND ISLAND STATE DETECTION

1. The equivalent circuit of grid

Grid acts as a load for PV generation system, and the grid at low frequency can be represented as an ideal voltage source $V_A(t)$ in series with $R_s$ and $L_s$, shown in Fig. 5(a). The model of grid at high frequency is illustrated in Fig. 5(b). The equivalent circuit of grid is applied to investigate the response to the components at fundamental frequency and high frequency.

2. Island state detection

Fig. 6 The high frequency equivalent circuit for island test

Based on the equivalent circuit at high frequency of grid shown in Fig. 5(b), a simplified equivalent circuit for island test is illustrated in Fig. 6, where the sum of terms in Equation (1) excluding fundamental component is represented as voltage source $V_{Ns}$, the inductor $L$ is the filter of the inverter, and resistance $R_1$ represents the loss of inductor $L$. PV generation system operated in grid connected state or island state can be simulated by switching $sw$. When $sw$ is tuned on, the system is in the grid connected state. When $sw$ is off, it’s in island state. In the experiment of the island test, resonant load ($R_L$, $C_L$ and $L_L$) is connected in parallel behaved as local load, which is recommended in IEEE Std. 929 and IEEE Std. 1547.1. In practice, the local load is selected whose quality factor is 1.25.

According Norton’s law, the high frequency equivalent circuit for island test shown in Fig. 6 can be simplified, as illustrated in Fig. 7(a), where the current source $i_{Ns}$ is equal to the voltage source $V_{Ns}$ divided by the impedance $\omega L + j R_1$, the inductive reactance of the inductor is much greater than its resistance when the component at high frequency is applied to the circuit, thus it’s easy to obtain that

$$Y_1 = \frac{1}{R_1 + j\omega L_1} + \frac{1}{R_2 + j\omega L_2} + \frac{1}{R_3 + j\omega L_3}$$

$$Y_1 = \frac{R_1 - j\omega L_1}{R_1^2 + (\omega L_1)^2} + \frac{R_2 - j\omega L_2}{R_2^2 + (\omega L_2)^2} + \frac{R_3 - j\omega L_3}{R_3^2 + (\omega L_3)^2}$$

(4)

The admittance of $Y_1$ is given by the following expression:

$$Y_1 = \frac{1}{R_1 + j\omega L_1} + \frac{1}{R_2 + j\omega L_2} + \frac{1}{R_3 + j\omega L_3}$$

$$Y_1 = \frac{R_1 - j\omega L_1}{R_1^2 + (\omega L_1)^2} + \frac{R_2 - j\omega L_2}{R_2^2 + (\omega L_2)^2} + \frac{R_3 - j\omega L_3}{R_3^2 + (\omega L_3)^2}$$

(5)

The inductive reactance of the inductor is much greater than its resistance when the component at high frequency is applied to the circuit, thus it’s easy to obtain that

$$R_1^2 + (\omega L_1)^2 \approx (\omega L_1)^2$$

$$R_2^2 + (\omega L_2)^2 \approx (\omega L_2)^2$$

$$R_3^2 + (\omega L_3)^2 \approx (\omega L_3)^2$$
The admittance of \( Y_1 \) can be approximately expressed as follows:

\[
Y_1 \approx \frac{1}{j\omega L_{eq}} + \frac{R_1}{(\omega L_1)^2} + \frac{R_r}{(\omega L_1)^2} + \frac{1}{j\omega} \left( \frac{1}{L_s} + \frac{1}{L_r} \right) \tag{6}
\]

Usually, in the island test, the value of inductor \( L_s \) is much greater than the value of inductor \( L_1 \) or \( L_r \), so the admittance of \( Y_1 \) can be further approximated as

\[
Y_1 \approx g + \frac{1}{j\omega L_{eq}}
\]

\[
g = \frac{R_1}{(\omega L_1)^2} + \frac{R_r}{(\omega L_1)^2} + \frac{R}{(\omega L)^2}
\]

where \( L_{eq} \) is equal to \( \frac{L_1 L_r}{L_1 + L_r} \).

Based on the Equation (7), an equivalent circuit is illustrated in Fig. 7(b). According to this equivalent circuit, the total admittance \( Y \) is calculated as follows:

\[
Y = (g + g) + \left( \frac{1}{j\omega L_{eq}} + j\omega C_{eq} \right)
\]

where, \( g \) is the reciprocal of \( R_L \).

Based on the above analysis, a simplified equivalent circuit, as illustrated in Fig. 7(c), is finally obtained. Thus, the total impedance can be expressed as

\[
Z = \frac{1}{Y} = \frac{1}{g + g} - \frac{1}{j\omega C_{eq}}
\]

\[
= \frac{R_{eq}}{1 + jQ_{eq} \left[ \frac{\phi}{\phi_{max}} - \frac{\phi_{max}}{\phi} \right]}
\]

where, \( \phi_{max} = \frac{1}{\sqrt{L_{eq} C_L}} \)

\[
R_{eq} = \frac{1}{g + g}, \quad Q_{eq} = R_{eq} \sqrt{C_L \cdot L_{eq}}.
\]

Solution for the voltage across the point of common coupling yields

\[
\dot{U}_{PCC} = \dot{I}_{SS} Z = \frac{\dot{U}_{SS}}{Z_{1}} Z = \frac{R_{eq}}{1 + jQ_{eq} \left[ \frac{\phi}{\phi_{max}} - \frac{\phi_{max}}{\phi} \right]} \tag{10}
\]

When the PV generation system is in grid connected state, the magnitude and phase frequency response of the output voltage across the point of common coupling are as follows:

\[
\frac{\dot{U}_{PCC}}{\dot{U}_{SS}} = \frac{R_{eq}}{\sqrt{R_{eq} + (\omega L_{eq})^2} \times \left[ 1 + Q_{eq} (\frac{\phi_{max}}{\phi_{max}} - \frac{\phi_{max}}{\phi}) \right]}
\]

\[
\Delta \phi = -\arctan \frac{1}{R_1} - \arctan Q_{eq} \left[ \frac{\phi}{\phi_{max}} - \frac{\phi_{max}}{\phi} \right] \tag{12}
\]
Table 1  The parameters both in simulation and experiment

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<th>parameter</th>
<th>value</th>
<th>parameter</th>
<th>value</th>
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<td>$R_L$</td>
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</tr>
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<td>$L_L$</td>
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<tr>
<td>$L_s$</td>
<td>112.4 u</td>
<td>$R_I$</td>
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</tr>
</tbody>
</table>

When the PV generation system is in island state, that’s to say that the switch $sw$ is turned off, the magnitude and phase frequency response of the output voltage across the point of common coupling are

$$\frac{U_{\text{PCC}}}{U_{\text{LS}}} = \frac{R_e}{\sqrt{R_e^2 + (\omega L_s)^2} \times \left[ 1 + Q_e^2 \left( \frac{\omega}{\omega_{\text{reson}}} - \frac{\omega_{\text{reson}}}{\omega} \right)^2 \right]}$$

$$\Delta \phi = -\arctan \frac{\omega L_s}{R_e} - \arctan Q_e \left( \frac{\omega}{\omega_{\text{reson}}} - \frac{\omega_{\text{reson}}}{\omega} \right)$$

where $\omega_{\text{reson}} = \frac{1}{\sqrt{L_s C_e}}$, $\omega_{\text{reson}} = \frac{R_e}{g_L + g}$, $Q_e = \frac{C_e}{L_s}$, $g = \frac{R_e}{(\omega L_s)^2}$, $g_L = \frac{1}{R_e}$.

3. On-line impedance estimation using harmonic injection

i. Perturbation

Equations (11) - (14) are expressed as analytical functions. The actual values are substituted into these equations to obtain numerical result using MATLAB software. The simulation parameters are shown in Table 1.

Substitution of the above parameters sketches the diagram of frequency response of Equations (11) - (14) in Fig. 8.

According to the Fig. 8, when the switch $sw$ is controlled to switch from forward-conduction to reverse-blocking, it’s obvious that the common point voltage’s magnitude varies suddenly in the range of 100 Hz - 1 kHz, and the common point voltage’s phase jumps suddenly in the range of 200 Hz t-3 kHz as well. That’s to
say, it’s wise to inject perturbation current whose frequency is in range of 200 kHz-3 kHz to detect whether the PV generation system is in island state or not. In this paper, 1 kHz perturbation current is injected.

According to the Fig. 8, when the switch \( sw \) is controlled to switch from forward-conduction to reverse-blocking, it’s obvious that the common point voltage’s magnitude varies suddenly in the range of 100 Hz - 1 kHz, and the common point voltage’s phase jumps suddenly in the range of 200 Hz - 3 kHz as well. That’s to say, it’s wise to inject perturbation current whose frequency is in range of 200 kHz - 3 kHz to detect whether the PV generation system is in island state or not. In this paper, 1 kHz perturbation current is injected.

ii. Calculation and experimental results

Based on the above analysis, the diagram of island detection method is proposed, as illustrated in Fig. 9. The phase detector is performed by the costas loop, as illustrated in Fig. 10, and the magnitude detector is shown in Fig. 11.

All the above diagrams are developed using DSP (TMS320F28335), and the structure of key element PLL is illustrated in Fig. 12. Experimental result of oscilloscope measurement of DSP-based control system is through DA converter, as shown in Fig. 13.

In the experiment, the component at 1 kHz is injected into grid current to detect whether the PV generation system is in island state or not. The parameters of experiment are shown in Table 1. The experimental result is shown in Fig. 14. In Fig. 14(a), CH1 is the control signal of switch \( sw \), and when this signal is high level, \( sw \) is turned on, and the PV generation system operates in grid connected state. When this signal is low level, \( sw \) is

Fig. 9 The diagram of proposed island detection method

Fig. 10 The diagram of phase detector realized by the costas loop
Fig. 11 The diagram of magnitude detector

Fig. 12 Single phase PLL for DSP implementation in phase detector and magnitude detector

Fig. 13 Measurement of signals of the DSP-based control system

Fig. 14 Experimental results: (a) output of magnitude detector and phase detector; (b) the grid current and the voltage of PCC point; (c) enlarged waveform

turned off, and the PV generation system operates in island state. Ch2 and Ch3 represent the output of magnitude detector and phase detector, respectively. It’s obvious that when the PV generation system operates in island state, both the value of output of magnitude detector and phase detector will exceed the thresholds.

The waveforms of grid current and voltage of the PCC point are illustrated in Fig. 14(b), and enlarged
waveforms are shown in Fig. 14(c). Compared to the grid current in Fig. 2, it is obviously noticed that the distortion of the grid current is reduced to the minimum in Fig. 14(b) and Fig. 14(c). That is to say, the proposed method to inject high frequency perturbation into grid current can detect island state well but reduce the distortion of the grid current to minimum.

IV. CONCLUSIONS

Usually, the low-frequency component is injected into grid current to detect whether the island state occurs or not but leading to a bit distortion of grid current. A new active anti-island approach is proposed which is suitable for single-phase grid-connected PV system. A small amount of current component at 1 kHz instead of low-frequency component is injected into grid current. By using DSP (TMS320F28335), the proposed the island detection method consisting of phase detector and magnitude detector is implemented. According to the experimental results, this method achieves the goal of anti-island detection and reduces the current distortion to the minimum. Of course that using a higher frequency injection implies an assumption that the grid impedance is linear on this frequency range. However, the estimation error caused by this assumption does not affect significantly the performance of the proposed method. Both the simulation and experimental results verify the feasibility.

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