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AN IMPROVED ACTIVE PHASE-SHIFT ISLANDING DETECTION METHOD BASED ON FUZZY ADAPTIVE PID ALGORITHM

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Abstract

In the process of islanding detection, the traditional positive feedback active frequency shift method takes a long time and affects the power quality. The islanding detection characteristics and detection principle of photovoltaic microgrid are analysed. Combined with the fuzzy adaptive PID detection, the feedback parameters are adjusted according to the frequency deviation and deviation change PCC rate to improve the islanding detection efficiency. A fuzzy adaptive PID control algorithm is used to optimise the feedback coefficient in real time. To meet the requirement that the detection error increases due to the constant change of system load. The algorithm introduces frequency difference feedback to optimise the feedback constant of island detection and improve the speed of island detection. The simulation results show that this method can not only quickly short the detection time but also reduce the blind area and improve the efficiency of islanding detection.

Key Words

PID, islanding, detection, adaptive, feedback coefficient

1. Introduction

Nowadays, more and more renewable energy is converted into electric energy, in which islanding detection technology is the normal operation of the power generation system. If the photovoltaic (PV) system cannot detect the failure status of the power grid effectively in a timely and effective manner and disconnect within a shorter time, it may endanger the personal safety of the entire distribution system and maintenance personnel. Considering the security and stability of the microgrid system, islanding detection is an essential part of the distributed power supply. The common connection point of common coupling (PCC) is between the microgrid and the distribution network. When the grid connection is switched to islanding, if the PV microgrid system cannot detect the island state quickly and effectively at the PCC switch and disconnect the microgrid from the public grid within a specified time, it will lead to system equipment loss or casualties [1], [2].

Traditional islanding methods can detect the changes in voltage amplitude and frequency by interfering with inverter-related parameters to determine whether islanding occurs in PV microgrids. After the power grid is disconnected, the frequency and phase of PCC point voltage are determined by the inverter output current and determined by the characteristics of the load. The feedback coefficient method is often used in the active phase-shifting islanding detection, which can improve the power quality. As the feedback coefficient of the traditional detection is set to a fixed value, the feedback coefficient cannot be automatically adjusted due to the change in PCC frequency, and the detection speed and accuracy need to be improved.

The PV microgrid islanding effect model is established and the basic principle of islanding detection is analysed. The islanding detection method is further optimised based on the traditional islanding detection principle. In view of the PV principle of islanding detection, combined with the principle of fuzzy adaptive proportional–integral –differential (PID) control, an improved islanding detection control strategy based upon fuzzy PID adaptive control is proposed. The test results show that this method can realise fast islanding detection when islanding occurs in the power grid. It has strong adaptability to the change of common point voltage and frequency and can improve the quality of output power [3].

2. Characteristic Analysis of Islanding Effect

When islanding occurs, the power flow is shown in Fig. 1.

As shown in Fig. 1, L, C, and R represent the inductance, capacitance, and resistance of the microgrid equivalent load, respectively; P refers to the active power; ΔP refers to the active power transmitted by the PV inverter to the grid under normal conditions; Q is the output reactive power; ΔQ is the reactive power transmitted to the power grid under normal conditions;

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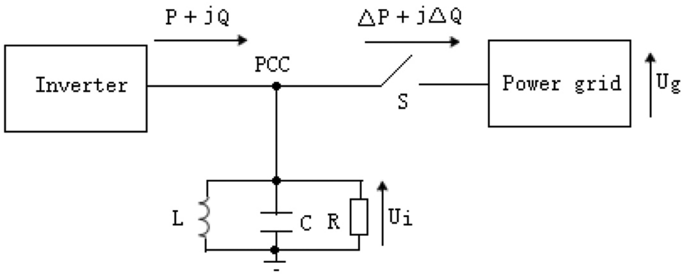

Figure 1. Characteristic structure of islanding effect.

U_g represents the grid voltage, and U_i represents the output voltage of the PV inverter [4].

2.1 Normal Operation of Power Grid

As shown in Fig. 1, under the normal working state of the power grid, it is equivalent to closing the PCC switch S. The active and reactive power outputs are provided to equivalent loads. The other part of the active and reactive power is transmitted to the power grid. The inverter load power balance:

$$\frac{{U_g}^2}{R} = P - \Delta P \tag{1}$$

$$\left[\frac{1}{\omega_g L_r} - \omega_g C_r\right] {U_g}^2 = Q - \Delta Q \tag{2}$$

where ω_g is the grid angular frequency.

2.2 Power Grid Shutdown

When the power grid is suddenly cut off, it is equivalent to opening the PCC switch S. As the output active power P and the reactive power Q of the inverter remain basically unchanged before and after S is turned off, the following conclusion can be drawn according to the power balance relationship:

$$\frac{{U_i}^2}{R} = P \tag{3}$$

$$\left[\frac{1}{\omega_i L_r} - \omega_i C_r\right] {U_i}^2 = Q \tag{4}$$

where ω_i is the angle of the inverter frequency. According to the balance relationship of the inverter output active power, (1) and (2) can be combined as follows:

$$\frac{\Delta P}{P} = 1 - \frac{{U_g}^2}{{U_i}^2} \tag{5}$$

Combined with (1)–(5), it can be deduced that:

$$\frac{\omega_i}{\omega_g}\frac{{U_g}^2}{{U_i}^2} = \frac{Q - \Delta Q + Q_c}{Q + Q_c \frac{\omega_i}{\omega_g}\frac{{U_i}^2}{{U_g}^2}} \tag{6}$$

where Q_c is the reactive power of the resonant capacitor in the resonant circuit. Combining with (5) and (6), the following results can be obtained:

$$\frac{\omega_i}{\omega_g}\frac{\Delta P}{P} - \frac{\Delta Q}{Q} = \left[\frac{{\omega_i}^2}{{\omega_g}^2} - 1\right]\frac{Q_c}{Q} + \frac{\omega_i}{\omega_g} - 1 \tag{7}$$

(6) and (7) show that when islanding occurs, the frequency and amplitude are related to the inverter active and reactive power.

2.3 Characteristic Analysis

When the islanding effect occurs, $U_g = U_i$, the inverter voltage remains unchanged. If ΔP and ΔQ are zero, (7) can be converted to (8):

$$\left[\frac{\omega_i}{\omega_g} - 1\right]\left(\frac{Q_c}{Q}\left[\frac{\omega_i}{\omega_g} + 1\right] + 1\right) = 0 \tag{8}$$

$\omega_g = \omega_i$ can be obtained from (8).

The above analysis shows that when the grid stops working, the inverter voltage or frequency will change. According to the change, the islanding effect can be determined [5].

3. Principle of Islanding Detection

When the islanding effect of the PV microgrid occurs, the inverter current will offset the voltage frequency of PCC. At this time, the inverter output current is:

$$i_{\text{inv}} = I\sin(\omega t + \theta) \tag{9}$$

where I is the effective value of the inverter output current; ω is the angular frequency of PCC, and θ is the added disturbance angle. The sine function expression of the added disturbance angle is:

$$\theta = \theta_m\left(\frac{\pi}{2}\cdot\frac{f - f_0}{f_m - f_0}\right) \tag{10}$$

where θ is the angle of disturbance; f is PCC frequency; f_m is the maximum frequency; f_0 is the power grid frequency, and θ_m is the maximum angle [6]. After the islanding effect, the separation of the power grid makes the clamping effect disappear. Due to the effect of positive feedback, the voltage frequency output by the inverter power supply will exceed the preset frequency threshold, triggering the over-frequency or under-frequency tripping of the relay protection device to successfully detect the islanding. To further improve the detection rapidity, an improved method is proposed [7], [8]:

$$\theta = k(f - f_0) + (f - f_0)\theta_0, \quad f \geq f_0 \tag{11}$$

$$\theta = k(f - f_0) + (f_0 - f)\theta_0, \quad f < f_0 \tag{12}$$

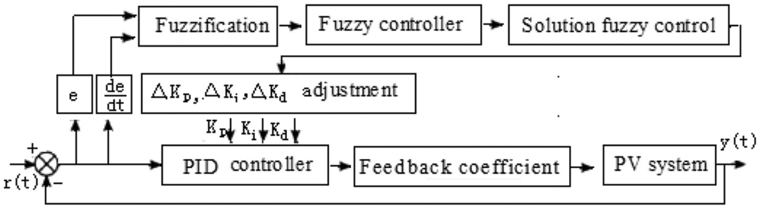

Figure 2. Controller structure diagram.

where k is the positive feedback coefficient. When the PCC frequency of the PV microgrid changes, the PCC voltage phase changes in the same direction. θ_0 is a small constant, whose purpose is that when the PV microgrid is converted from grid-connected to islanding, the small offset can accelerate the phase offset to improve the islanding detection efficiency of the PV microgrid.

However, this method has defects. As the feedback coefficient is within the value range, it is usually fixed. In fact, the feedback coefficient k has a corresponding relationship with the load, which is difficult to determine. For the feedback coefficient, the islanding monitoring system needs to be adaptively changed according to different loads. Due to the change of PCC voltage and frequency of PV microgrid, traditional methods cannot adaptively adjust the feedback coefficient, and the detection accuracy and efficiency of PV microgrid decrease in a certain range [9].

4. Fuzzy Adaptive PID Optimisation

4.1 Design of Controller

The scale factor of the traditional controller is fixed, which influences the steady state and dynamic performance. Fuzzy adaptive PID control is based on the traditional fuzzy control, using the change of the input variables to optimise and adjust the proportional factor of the fuzzy control system. This improved control strategy enables the scale factor to automatically adapt to the changes of input [10].

When the grid is disconnected, the load characteristics in the actual grid environment are unknown. In islanding detection, the fixed feedback coefficient k has a corresponding relationship with the load, which is difficult to determine. The frequency deviation and frequency change rate of the PCC point voltage will increase with the increase of external disturbance. The controller structure is shown in Fig. 2.

Figure 2 shows that the system can adjust the scale factor adaptively in real time according to the changes of input variables. The deviation e between the PCC frequency f_{pcc} and the grid voltage rated frequency f_g and the change rate ec of e are taken as the input, and the feedback coefficient K is taken as the output variable. According to the requirements of frequency deviation of small capacity distributed systems, the frequency variation in one power grid cycle cannot exceed 0.5 Hz, setting the frequency deviation $e \in [-0.5, 0.5]$ and frequency variation rate $ec \in [-50, 50]$. The PCC point voltage and frequency of the PV microgrid are detected at all times. The current sampling value and the last sampling value are represented by n and $n-1$, respectively [11], [12].

The fuzzy adaptive PID algorithm continuously optimises and adjusts the three PID parameters to output the optimal PID scale factor parameters. The optimal feedback coefficient of islanding detection is obtained to achieve the automatic optimisation of the feedback coefficient.

4.2 Fuzzy Control Parameters

The error e and the corresponding error rate of change ec are the inputs of the fuzzy controller. The proportional coefficient variation ΔK_p, the integral coefficient variation ΔK_i, and the differential coefficient variation ΔK_d are the outputs. In the islanding detection control, $[-3, +3]$ is used to represent the basic universe of difference e and error rate of change ec. The membership functions are all set as triangles.The fuzzy subsets of e, ec, ΔK_p, ΔK_i, and ΔK_d are set to {NL, NC, NP, ZE, PP, PC, PL}, which are, respectively, represented as {Negative Large, Negative Centre, Negative Petty, Zero, Positive Petty, Positive Centre, Positive Large}.

4.3 Establishment of Control Parameter Rule Table

The establishment table is the core problem of the fuzzy controller, which is mainly obtained by summarising the technical knowledge of engineering designers and the practical operation experience of the field operators. When establishing fuzzy control rules, the error should be minimised to ensure the system stability. Based on the influence characteristics of three parameters on the system during the PV microgrid islanding detection, the following regulation rules are formulated:

1. Proportional regulation can quickly reduce the steady-state error in time. Larger proportional adjustment coefficient can improve the response speed of the system, and too large will vibrate the system;
2. The magnitude of the integral adjustment coefficient will affect the overshoot. When the integral coefficient is too large, the steady-state error cannot be eliminated and the effect cannot be achieved. When the integral coefficient is too small, the function of the integral regulation module is large, leading to overshoot and oscillation;
3. For differential regulation coefficient link, it will affect the dynamic characteristics. If the adjustment time is

Table 1
The Fuzzy Control Rules of ΔK_p

ec e	NL	NC	NP	ZE	PP	PC	PL
NL	PL	PL	PC	PC	PP	ZE	ZE
NC	PL	PL	PC	PP	PP	ZE	NP
NP	PC	PC	PC	PP	ZE	NP	NP
ZE	PC	PC	PP	ZE	NP	NC	NC
PP	PP	PP	ZE	NP	NP	NC	NC
PC	PP	ZE	NP	NC	NC	NC	NL
PL	ZE	ZE	NC	NC	NC	NL	NL

Table 2
The Fuzzy Control Rules of ΔK_i

ec e	NL	NC	NP	ZE	PP	PC	PL
NL	NL	NL	NC	NC	NP	ZE	ZE
NC	NL	NL	NC	NP	NP	ZE	ZE
NP	NL	NC	NP	NP	ZE	PP	PP
ZE	NC	NC	NP	ZE	PP	PC	PC
PP	NC	NP	ZE	PP	PP	PC	PL
PC	ZE	ZE	PP	PP	PC	PL	PL
PL	ZE	ZE	PP	PP	PC	PL	PL

Table 3
The Fuzzy Control Rules of ΔK_d

ec e	NL	NC	NP	ZE	PP	PC	PL
NL	PP	NP	PC	NL	NL	NC	PP
NC	PP	NP	NL	NC	NC	NP	ZE
NP	ZE	NP	NC	NC	NP	NP	ZE
ZE	ZE	NP	NP	NP	NP	NP	ZE
PP	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PC	PL	NP	PP	PP	PP	PP	PL
PL	PL	PC	PC	PC	PP	PP	PL

too long and too small, the deviation of the system will increase [13].

The rules are shown in Tables 1–3.

4.4 Fuzzy Reasoning

According to the problems in the practical application of the islanding detection control system and the treatment methods under different error conditions, a Mamdani reasoning method is proposed based on the fuzzy adaptive conventional operation law. The fuzzy reasoning for PID parameters is carried out, respectively. Writing the above rules in the format of if...then..., we will obtain a total of 49 rules. For example, the fuzzy control rules are as follows:

$$\begin{aligned}&\mathrm{R1{:}\ IF\ e} = \mathrm{NL\ and\ ec} = \mathrm{NL\ THEN}\ \Delta \mathrm{K_p} = \mathrm{LB},\\ &\quad \Delta \mathrm{K_i} = \mathrm{NL},\ \Delta \mathrm{K_d} = \mathrm{PP}\end{aligned} \tag{13}$$

Rn:......

$$\begin{aligned}&\mathrm{R49{:}\ IF\ e} = \mathrm{PL\ and\ ec} = \mathrm{PL\ THEN}\ \Delta \mathrm{K_p} = \mathrm{NL},\\ &\quad \Delta \mathrm{K_i} = \mathrm{PL},\ \Delta \mathrm{K_d} = \mathrm{PL}\end{aligned} \tag{14}$$

The islanding detection and control system of the PV microgrid adopts Mamdani's reasoning method for fuzzy reasoning and decision making. Then, the output needs to be defuzzified based on the fuzzy rules. In this study, the centre of gravity method is used to defuzzify the island control system. The formula is as follows:

$$R = \frac{\sum_i \left[\gamma(\gamma_i) \times \gamma_i\right]}{\sum_i \gamma(\gamma_i)} \tag{15}$$

where R is the precise value after defuzzification; γ_i is the fuzzy variable element, and $\gamma(\gamma_i)$ is the membership of the corresponding element.

Based on the rule base and deduction of the fuzzy system, the PID controller parameters corrected in each sampling period are calculated after the fuzzy processing is completed:

$$\begin{cases} K_p = K_p^{/} + \Delta K_p \\ K_i = K_i^{/} + \Delta K_i \\ K_d = K_d^{/} + \Delta K_d \end{cases} \tag{16}$$

where $K_p^{/}$, $K_i^{/}$, and $K_d^{/}$ are three initial values of the fuzzy adaptive PID control parameters for island detection. For the output revised values K_p, K_i, and K_d obtained by the fuzzy adaptive control rule table, the processing formula of output is as follows:

$$k(i) = K_p e(i) + K_i \sum e(i) + K_d ec(i) \tag{17}$$

where $k(i)$ is the feedback control number of island detection. $e(i)$ and $ec(i)$ are the system frequency error and error rate of change, respectively. The implementation steps are summarised as follows [14]:

1. The collected error and error rate of change are input into the fuzzy controller;
2. Fuzzification, fuzzy reasoning, and clarity processing, and modify the output corresponding to the change;
3. The PID controller adds the three parameters to the corresponding parameters at the same time to obtain new PID controller parameters, so as to realise the

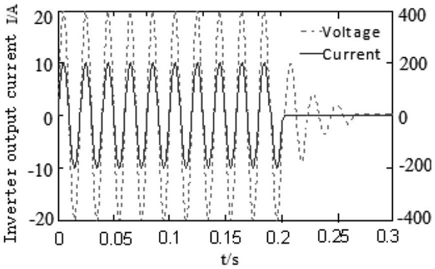

Figure 3. Islanding detection current waveform under traditional algorithm.

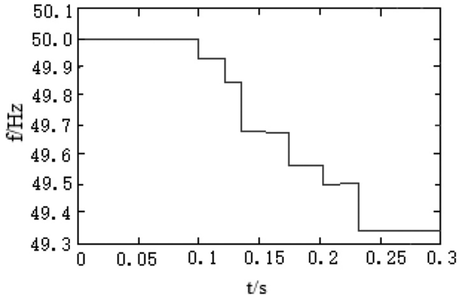

Figure 4. Islanding detection frequency waveform under traditional algorithm.

optimal control of the PV microgrid islanding detection feedback coefficient in real time.

5. Simulation Analysis

In order to verify the effectiveness of strategy, an islanding detection model is established through Matlab simulation. The simulation model is mainly composed of islanding detection module and fuzzy PID module. The model parameters are set as: 380V DC bus voltage, 220V grid voltage, and 50 Hz frequency [15], [16].

The power grid is disconnected in 0.1 s, and the threshold range of over-frequency and under-frequency protection is 49.5 Hz–50.5 Hz. The traditional algorithm and fuzzy adaptive PID algorithm are simulated, respectively. Figures 3 and 4, respectively, show the changes of inverter current and frequency after power failure of the traditional algorithm.

It can be seen from Figs. 3 and 4 that the traditional algorithm can detect the islanding state of the PV microgrid at 0.201 s, and the detection time is 0.101 s.

The simulation waveform optimised by fuzzy adaptive PID control is shown in Figs. 5 and 6.

As shown in Figs. 5 and 6, after power failure at 0.1 s, the disturbance direction is determined first, and then the small disturbance deviation generated by the improved algorithm is added continuously to accelerate the frequency offset under the action of positive feedback until it exceeds the threshold, and quickly trigger the over-under-frequency protection. At the same time, the inverter current is cut off and successfully detected at 0.149 s, and the detection time is only 0.049 s. After the adaptive PID optimisation, the active phase-shifting detection system shortens the islanding detection time and improves the islanding detection efficiency [17], [18].

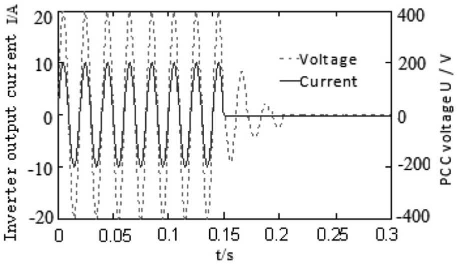

Figure 5. Islanding detection current waveform under the improved algorithm.

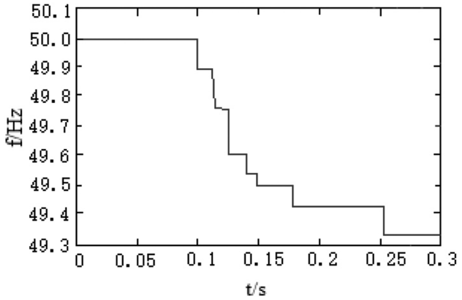

Figure 6. Islanding detection current waveform under the improved algorithm.

6. Conclusion

Based on the fuzzy adaptive control theory, this paper proposes a fuzzy adaptive phase shift islanding detection algorithm. In the traditional islanding detection methods, the feedback coefficient is generally a fixed constant, and the detection effect is poor. The new algorithm introduces the feedback of frequency difference to improve the detection speed. Through the automatic adjustment of the three parameters of PID, the optimal feedback parameters are found for different working conditions in island detection, so that island detection can be realised quickly. Under the same conditions, the traditional islanding detection time is 0.101 s, while that based on the fuzzy adaptive PID control is 0.049 s. Compared with the traditional algorithm, the method in this paper can shorten 0.052 s, which can improve the power quality and meet the requirements of the national standard. The islanding detection time is shortened and the influence of power grid fluctuation on load operation is avoided to a certain extent. The islanding detection method has strong adaptability, fast detection speed, and improved the quality of output power.

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