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Frequency Regulation of Alternating Current Microgrid Based on Hierarchical Control Using Fuzzy Logic

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Abstract: An alternating current (AC) microgrid is a system that integrates renewable power, power converters, controllers and loads. Hierarchical control can manage the frequency of the microgrid to prevent imbalance and collapse of the system. The existing frequency control methods use traditional proportion integration (PI) controllers, which cannot adjust PI parameters in real-time to respond to the status changes of the system. Hierarchical control driven by fuzzy logic allows real-time adjustment of the PI parameters and the method used a two-layer control structure. The primary control used droop control to adjust power distribution, and fuzzy logic was used in the voltage loop of the primary control. The secondary control was added to make up for frequency deviation caused by droop control, and fuzzy logic was used in the secondary frequency control to deal with the dynamic change of frequency caused by the disturbances of loads. The proposed method was simulated in Matlab/Simulink. In the primary control, the proposed method reduced the total harmonic distortion (THD) of two cycles of the output voltage from 4.19% to 3.89%; in the secondary control, the proposed method reduced the frequency fluctuation of the system by about 0.03 Hz and 0.04 Hz when the load was increased and decreased, respectively. The results show that the proposed methods have a better effect on frequency maintenance and voltage control of the AC microgrid.

Key words: fuzzy logic; hierarchical control; frequency regulation; droop control; alternating current (AC) microgrid

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0 Introduction

A microgrid is a small power system composed of distributed generation (DG), energy storage equipment, loads, power electronic converters, protection devices and control devices. It is a relatively independent system,

which can realize self-control and present the characteristics of low inertia and low capacity in terms of its attributes. It is suitable for application on islands, remote frontiers and factories. Microgrid has the advantages of clean and low energy loss compared with the traditional large grids. However, the frequency of the alternating current (AC) microgrid is a global variable, if the control of frequency is not effective, it will make the whole system out of balance or even collapse.

Nowadays, hierarchical control based on three-layer control has become the mainstream control scheme of microgrids. The primary control focuses on power distribution and local system stability; the secondary control is used to restore the state deviation caused by the primary control and serves the grid connection; the tertiary control concerns the power flow and its economic benefits. Concerning hierarchical control of microgrids, Mohiti et al.^[1] formulated a hierarchical frequency control structure with a two-stage robust optimization model of microgrids. Gong et al.^[2] proposed a distributed cooperative control strategy composed of primary droop control and a secondary distributed algorithm. Yin et al.^[3] summarized hierarchical control strategies of AC and direct current (DC) microgrids involving different secondary control structures. Adineh et al.^[4] provided a harmonic suppression method from the perspective of hierarchical control. Khongkhachat et al.^[5] reviewed hierarchical control strategies of AC microgrid. Guan et al.^[6] proposed a hierarchical control system based on an autonomous current-sharing controller. Li et al.^[7] proposed a hierarchical control of photovoltaic inverters triggered by distributed events to track maximum power generation. Heyderi et al.^[8] proposed a model predictive control method for distributed hierarchical control of microgrids.

However, the existing methods for the primary and

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secondary control are almost based on proportion integration (PI) controllers. The parameters of these controllers cannot be dynamically adjusted in real-time, which cannot respond to the changes in the system state. Liang et al.^[9] and Fu et al.^[10] proposed DC microgrid control methods based on fuzzy control to change the droop coefficients. Shan et al.^[11] proposed a distributed secondary fuzzy control method for microgrids. Chowdhury et al.^[12] designed a virtual synchronous generator control scheme based on a secondary fuzzy controller. Long et al.^[13] combined fuzzy control and model predictive control for virtual synchronous generator technology, resulting in the reduction of frequency fluctuation when loads change. Baghaee et al.^[14] studied the significant bus voltage drops solved by adjusting the reactive power reference value using a fuzzy controller. Neves et al.^[15] proposed a multi-task secondary fuzzy controller. Jafari et al.^[16] designed a fuzzy controller to determine the operation mode of microgrids through the charging state and power of the battery and energy cost errors. Chen et al.^[17] combined fuzzy control with proportion integration differentiation (PID) control for constant force control of industrial robot belts. Mao et al.^[18] studied a nonlinear voltage droop gain coefficient function based on virtual resistors by using multivariable Takagi-Sugeno (T-S) fuzzy logic, which realized coordinated power distribution of photovoltaic cells and voltage stability of DC bus.

To sum up, there is a lot of research on hierarchical control methods of microgrids and the application of fuzzy control in microgrids. However, the research on the unified and coordinated hierarchical control of microgrids through fuzzy control is not comprehensive and sufficient, especially through simple and mature fuzzy logic to continuously optimize the bottom-up hierarchical control structure of microgrids. Therefore, this paper will conduct a detailed study of this issue.

The main research contributions of this paper are listed as follows.

1) Fuzzy control is used in primary control to reduce the total harmonic distortion (THD) of the microgrid's

output voltage and to improve power quality.

2) Fuzzy control is applied to secondary control to minimize frequency fluctuation during distributed generations (DGs) and load change in the microgrid.

1 Hierarchical Control and Hierarchical Fuzzy Control of Microgrids

1.1 Hierarchical control of microgrids

The microgrid's structure is shown in Fig. 1. In Fig. 1, the connection of two DGs is used as an example to illustrate the internal structure and composition of a microgrid.

Figure 1 illustrates the two-layer control of microgrids, where L and C are the inductor and the capacitor in the main circuit, respectively; i_L is the output current; i_{abc} and u_{abc} are three-phase current and voltage, respectively; P and Q are the active power and reactive power of the microgrid calculated by the PQ calculation module; f_0 , U_0 , P_0 and Q_0 are the reference frequency, reference voltage, reference active power and reference reactive power of the droop control, respectively; U_{dref} , U_{qref} , I_{dref} and I_{qref} are the reference voltage and reference current components output by the controllers in the dq coordinate system. PWM is short for pulse width modulation, which is used to control the on-time of transistors in the inverter. PLL is short for phase-locked loop. U is the bus voltage of the microgrid. $\Delta\omega$ and ΔE are the adjustment values of the frequency and voltage generated by the secondary controller, which act in the primary control. In the main circuit, the DC of DG is converted into AC by an inverter, subsequently, AC is filtered by a filter. In the primary control circuit, the abc coordinate is converted into the dq coordinate, then the calculated active power and reactive power are input into the droop equation. The secondary control obtains the frequency and amplitude of the microgrid bus voltage through the PLL. The secondary control completes the compensation of frequency and voltage drop caused by droop control in the primary control, which restores the frequency and voltage to the target value.

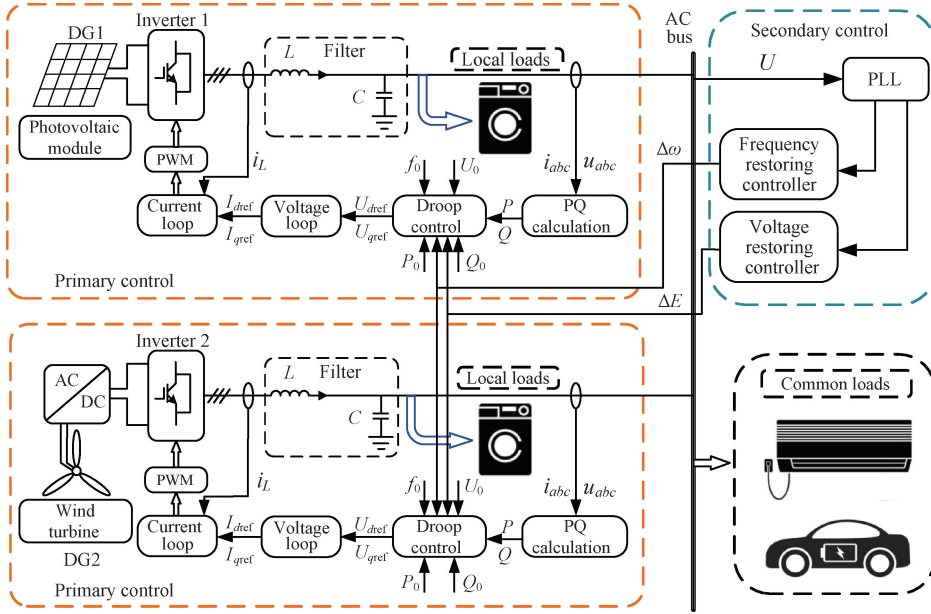


Fig. 1 A microgrid with multiple energy sources and converters

1.2 Primary control

The droop control strategy has been extensively used in microgrids due to its similarity with the primary frequency modulation of traditional generators. The control principle is depicted in Fig. 2.

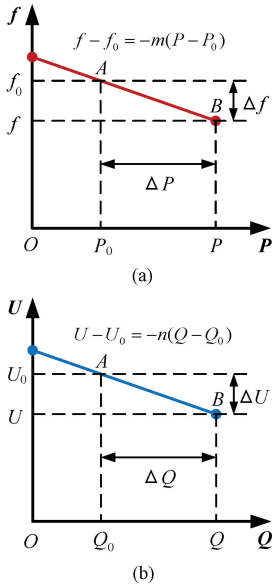


Fig. 2 Droop characteristic curves: (a) P - f droop characteristic; (b) Q - U droop characteristic

When the active and reactive power of the microgrid change, the system adjusts its output frequency and voltage amplitude according to the P - f and Q - U droop curves, respectively. The equation used in the process is given by

$$\begin{cases} f - f_0 = -m(P - P_0), \\ U - U_0 = -n(Q - Q_0), \end{cases} \quad (1)$$

where f and U are the output frequency and voltage of the inverter, respectively; f_0 and U_0 are the reference values of frequency and voltage, respectively; m and n are the active and reactive droop control coefficients, respectively.

Figure 3 is the structure diagram of droop control, where 50 and 380 are the target frequency and voltage amplitude of the microgrid, respectively; Δf and ΔU are the adjustment values of the frequency and voltage, respectively.

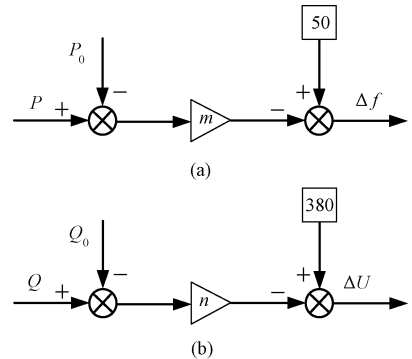


Fig. 3 Structure diagram of droop control: (a) P - f droop control; (b) Q - U droop control

To achieve a better control effect of droop control, it is necessary to calculate the output power of DGs, and dq coordinate system is used to simplify the calculation process, the calculation equation is

$$\begin{cases} P = u_{od}i_{od} + u_{oq}i_{oq}, \\ Q = u_{od}i_{oq} - u_{oq}i_{od}, \end{cases} \quad (2)$$

where u_{od} , u_{oq} , i_{od} and i_{oq} represent the components of voltage and current in the dq coordinate, respectively.

Figure 4 illustrates the structure of the voltage and

current double closed-loop control, where u_{abc} and i_{abc} are the output voltage and current of the inverter in the abc coordinate system, respectively; u_{odq} and i_{odq} are the output voltage and current of the inverter in dq coordinate system, respectively; u_{refdq} is the output reference voltage

of the droop control. The outer voltage loop compares u_{odq} with u_{refdq} , and the difference is continuously reduced through the controller. The output value of the voltage loop is then compared with i_{odq} , which improves the system's dynamic response capability.

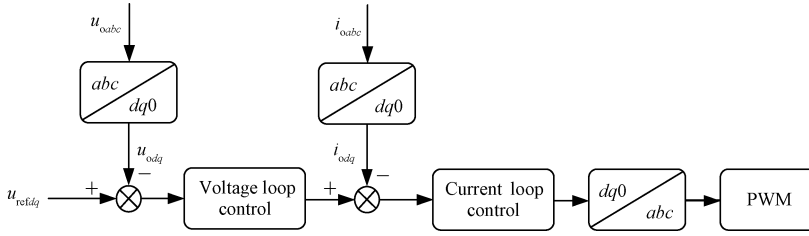


Fig. 4 Diagram of voltage and current double closed-loop control

1.3 Secondary control

The frequency and voltage amplitude of microgrids will decrease because the primary control uses droop control. Therefore, the secondary control is necessary to recover the drop. The secondary control initially obtains the actual frequency and amplitude of the output voltage through PLL, and the actual values are compared with the reference values. The deviation is compensated by PI controllers, resulting in an output voltage close to the reference value. The mathematical expression of the control principle is

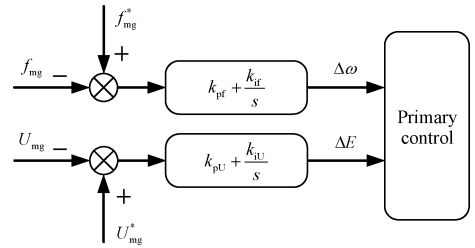


Fig. 5 Secondary control diagram of voltage and frequency

$$\begin{cases} \Delta\omega = k_{pt}(f_{mg}^* - f_{mg}) + k_{if} \int (f_{mg}^* - f_{mg}) dt, \\ \Delta E = k_{pU}(U_{mg}^* - U_{mg}) + k_{iU} \int (U_{mg}^* - U_{mg}) dt, \end{cases} \quad (3)$$

where k_{pt} and k_{if} represent the proportional and integral parameters of the PI controller used for frequency compensation in the secondary control, respectively; k_{pU} and k_{iU} represent the proportional and integral parameters of the PI controller used for voltage amplitude compensation in the secondary control, respectively; f_{mg} and U_{mg} are the output frequency and voltage amplitude of microgrids, respectively; f_{mg}^* and U_{mg}^* are the reference values of frequency and voltage amplitude, respectively; $\Delta\omega$ and ΔE are the regulated values of the frequency and voltage amplitude, respectively.

Figure 5 displays the diagram of the secondary control derived from the principles mentioned above. Initially, the measured frequency f_{mg} and voltage amplitude U_{mg} of the microgrid's output voltage are respectively compared to the frequency reference value f_{mg}^* and voltage amplitude reference value U_{mg}^* . S is a complex variable in the Laplace transform. The output frequency adjustment value $\Delta\omega$ and voltage amplitude adjustment value ΔE are then regulated by the PI controller.

1.4 Primary fuzzy control

The traditional primary control in the voltage and current loop employs the PI controller, which is known for its simplicity and good robustness, and wide application in various fields. By setting appropriate parameters, a good control effect can be achieved. However, the PI parameters remain fixed throughout the control process, and the optimization of the parameters cannot be guaranteed with the change of the control variables, leading to reduced control effectiveness. To address this issue, a fuzzy PI control method is recommended. This allows the fuzzy controller to continuously adjust the parameters of the PI controller for optimal control of the microgrid's output frequency.

The design process of the fuzzy controller comprises fuzzification, fuzzy reasoning and defuzzification. The fuzzy controller consists of membership functions and fuzzy rules. The membership functions refer to the membership relation of variables in a fuzzy set, and their determination is subjective. This study utilizes the triangular membership function, whose functional relationship is depicted in Fig. 6. The fuzzy rules are the form of "If x is A , then y is B ", which are the keys to fuzzy control. The fuzzy rules determined based on the membership functions are presented in Table 1, e represents the deviation between the reference voltage and the output voltage of the inverter, which is used as input of the fuzzy controller; Δe is the rate of change of e ;

NB, NS, ZO, PS and PB are fuzzy marks representing deviation values' sizes, which are "negative big", "negative small", "zero", "positive small" and "positive big", respectively.

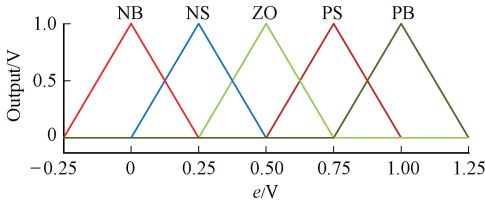


Fig. 6 Membership function

This research uses the basic fuzzy rules to explore the potential of fuzzy-driven effects, reducing the complexity of control system design and improving algorithm reliability and implementability. Figure 7 is the fuzzy logic surface diagram drawn according to the fuzzy rules in Table 1.

Table 1 Fuzzy rules of primary fuzzy controller

e/V	$\Delta e/(V/s)$				
	NB	NS	ZO	PS	PB
NB	NB	NS	NS	NS	ZO
NS	NS	NS	ZO	ZO	ZO
ZO	NS	ZO	ZO	PS	PS
PS	NS	ZO	PS	PS	PS
PB	ZO	ZO	PS	PS	PB

To obtain the controlled system's output, the final defuzzification process is required. Following these ideas, this study adds a fuzzy controller to the voltage loop's PI controller and builds a simulation model of primary control with fuzzy PI control. The configuration diagram of primary fuzzy control is drawn in Fig. 8.

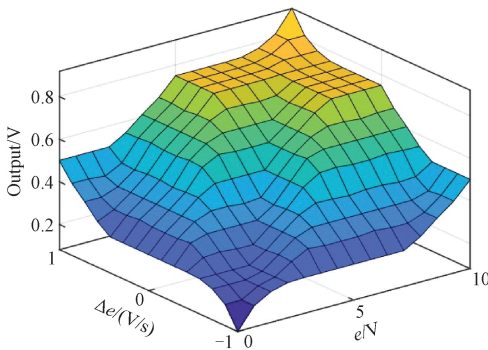


Fig. 7 Fuzzy logic rule surface diagram of primary fuzzy control

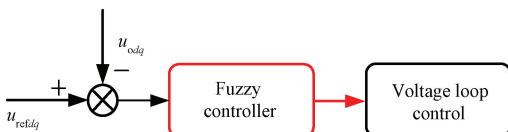


Fig. 8 Configuration diagram of primary fuzzy control

1.5 Secondary fuzzy control

Various methods are available for the secondary control of microgrids, such as model predictive control and PI control. However, this study utilizes and improves traditional PI control methods. The secondary control adopts a fuzzy PI mode to adjust the PI controller's parameters through the fuzzy controller's output. The control principle of the fuzzy controller has already been introduced in the preceding discussion. The design of the fuzzy controller in the secondary control is identical to that in the primary control.

The frequency and amplitude of the output voltage obtained via PLL are compared with reference values in the secondary control, and the deviation is taken as the input of the fuzzy controller. The output value is multiplied by the gain coefficient and connected to the PI controller. The output of the secondary fuzzy control is given by

$$\begin{cases} e_E = K_{eE}(E_0 - E), \\ e_\omega = K_{e\omega}(\omega_0 - \omega), \end{cases} \quad (4)$$

where E_0 and ω_0 represent the references of the voltage amplitude and frequency of the secondary fuzzy control, respectively; E and ω denote the voltage amplitude and frequency measured at the common connection point, respectively; K_{eE} and $K_{e\omega}$ are the gain coefficients of voltage regulation and frequency regulation, respectively; e_E and e_ω are defined using triangular membership functions and are served as inputs to the voltage fuzzy controller and frequency fuzzy controller, respectively. The configuration diagram of secondary fuzzy control is depicted in Fig. 9, the output voltage's amplitude and frequency of the microgrid are obtained through PLL and compared with the reference values. Then the difference values e_E and e_ω are entered into the fuzzy controller, $\Delta\omega$ and ΔE are frequency adjustment value and voltage amplitude adjustment value respectively, which act in the primary control.

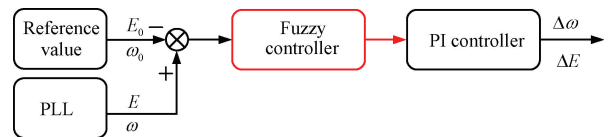


Fig. 9 Configuration diagram of secondary fuzzy control

Table 2 displays the input a and output frequency of the secondary fuzzy controller, similar to the primary fuzzy control. Furthermore, Fig. 10 illustrates the fuzzy logic rule surface of the secondary fuzzy control. Subsequently, fuzzy-PI control is executed, and the output is transmitted to the primary control for the final adjustment of the output voltage.

Table 2 Fuzzy rules of secondary fuzzy controller

a/Hz	NB	NS	PS	PB
Output/Hz	PB	PS	NS	NB

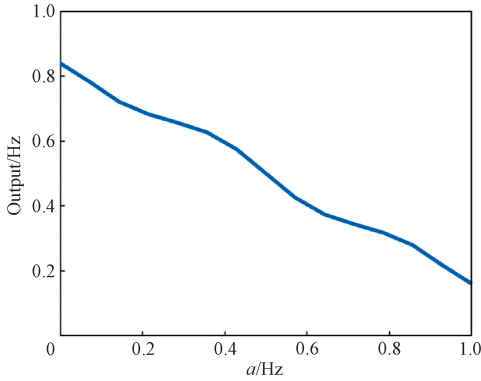


Fig. 10 Fuzzy logic rule surface diagram of secondary fuzzy control

2 Verification

2.1 The settings of the system parameters

To verify the feasibility and effectiveness of the proposed methods, the microgrid illustrated in Fig. 1 is simulated and implemented in MATLAB/Simulink. The system parameters are listed in Table 3, k_p and k_i are the proportional and integral coefficients of the PI controller of the primary, k_{eEp} , k_{eEi} , k_{ewp} and k_{ewi} are the proportional coefficients and integral coefficients of the voltage PI controller and frequency PI controller in secondary fuzzy control. The microgrid system contains two DGs, denoted as DG1 and DG2, which form an AC common bus through inverters and filters, supplying local and common AC loads within the system. Each DG is equipped with primary and secondary controllers, as well as fuzzy controllers for each control level. Figure 11 shows the load distribution diagram of the microgrid.

Table 3 System settings and control parameters

Description	Value
Bus voltage	DC, 1 kV; AC, 380 V (Vrms, phase-phase), ($f_0 = 50$ Hz)
AC-side filter	$L = 0.9$ mH, $C = 250$ μF
Default loads	Local loads, $P_{DG1} = 10$ kW, $P_{DG2} = 10$ kW; common loads, $P_C = 20$ kW
Droop control	$m = \frac{3}{70000}$, $n = \frac{4}{11000}$; $P_0 = Q_0 = 0$
Primary control PI parameters	Outer voltage loop, $k_p = 8$, $k_i = 12$; inner current loop, $k_p = 0.24$, $k_i = 0.01$
Secondary control PI parameters	$k_{pf} = 0.5$, $k_{if} = 1.2$; $k_{pU} = 0.5$, $k_{iU} = 1.6$; $k_{eEp} = 0.6$, $k_{eEi} = 60$; $k_{ewp} = 0.56$, $k_{ewi} = 54$

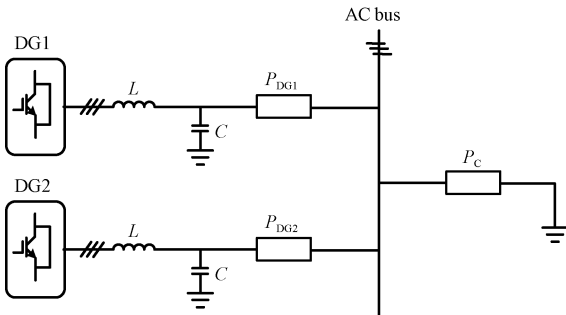


Fig. 11 Load distribution diagram of microgrid

2.2 Simulation results of hierarchical control on and off using fuzzy control

Figure 12 illustrates the output voltage waveform in the primary control, showing small fluctuations in its sine wave. A, B and C are each phase of the three-phase output voltage by using PI control. D, E and F are each phase of the three-phase output voltage by using the proposed fuzzy control (Fuzzy-PI). The output waveform using Fuzzy-PI has been significantly improved, becoming

smoother and closer to the standard sine wave. That is, the THD value reduces from 4.19% in Fig. 13 (a) to 3.89% in Fig. 13 (b) (quality analysis of sine waveforms of two cycles starting at 0.21 s). In Fig. 13, f_{sam} is the sampling frequency; M represents the percentage of the amplitude of the harmonic relative to the amplitude of the fundamental wave; F represents the fundamental amplitude; U_{thd} is the THD of the voltage.

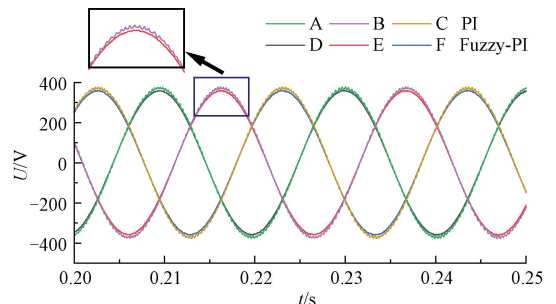


Fig. 12 Real-time output voltage waveform of DG1

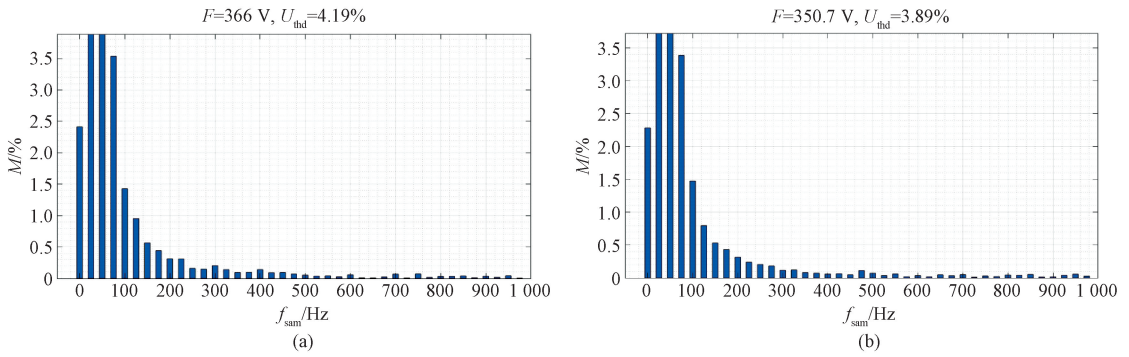


Fig. 13 Harmonic analysis of output voltage waveform: (a) using traditional PI method; (b) using Fuzzy-PI method

Figure 14 displays the frequency analysis using the traditional PI and the Fuzzy-PI method. Figure 14 (a) shows the system control performance under DG3 cut-in and cut-out. Before 0.5 s, DG1 and DG2 were operational within the microgrid, resulting in an output frequency of approximately 49.16 Hz. Upon the connection of a new DG, specifically DG3, at 0.5 s, the frequency spikes before stabilizing at 49.30 Hz. At 2.0 s, DG3 is removed and the frequency drops back to around 49.16 Hz. During the process of adding DG3 to the system, it is evident that the proposed primary fuzzy control experiences a lower overshoot than that of the traditional PI method. Quantitatively speaking, the frequency value of the maximum transient offset has decreased from 49.73 Hz to 49.48 Hz.

Figure 14 (b) illustrates the effect of secondary control on the system frequency when it is turned on and off. In Fig. 14(b), the secondary control is initiated at 1.0 s and turned off at 3.0 s. It can be seen that the Fuzzy-PI method can quickly and smoothly reach the reference value of the system frequency, while the traditional PI method cannot reach a steady state at 3.0 s.

Between approximately 1.2 s and 1.6 s, the traditional PI method reaches the maximum of 51.00 Hz under the frequency limit to protect the safety of the system. In Fig. 14 (c), the secondary control turns off at 8.0 s. The frequency can remain continuously stable by using the Fuzzy-PI method. It is also evident that the traditional PI method only reaches the reference value at 7.0 s. The comparison results fully demonstrate that the Fuzzy-PI method has the advantages of being faster and smoother than the traditional PI method.

Figure 14 (d) shows the control performance of the system when load increases and decreases. Both PI and Fuzzy-PI methods can stabilize the frequency at the rated value of 50.00 Hz. However, the Fuzzy-PI method has better transient performance when the load changes, with a smaller overshoot value and faster reaching the stable rated value. Specifically, the Fuzzy-PI method has a minimum value of 49.76 Hz when the load increases, which is higher than the traditional PI method's 49.73 Hz. When the load decreases again, the Fuzzy-PI method has a maximum value of 50.20 Hz, which is lower than the traditional PI method's 50.24 Hz.

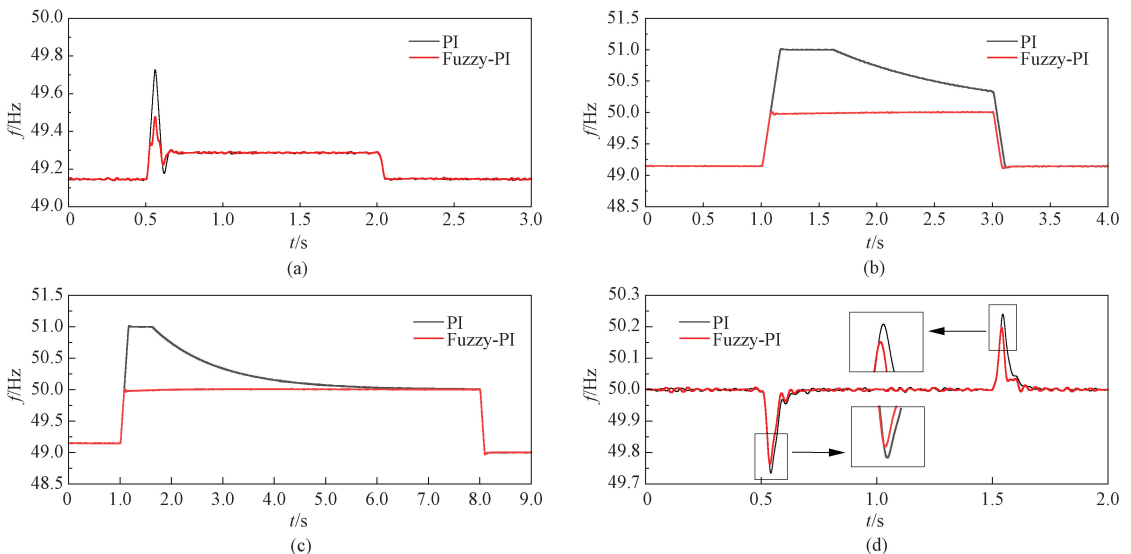


Fig. 14 Frequency analysis using traditional PI and Fuzzy-PI method; (a) system control performance under DG3 cut-in and cut-out; (b) system control performance under secondary control on and off; (c) system control performance after stabilization under secondary control on and off; (d) system control performance when load increases and decreases

3 Conclusions

This paper proposes a hierarchical control structure that utilizes fuzzy logic to enhance power quality in both primary control and secondary control. The primary and secondary controls, driven by fuzzy logic, allow for self-adaptive adjustments of the hierarchical control coefficients, enabling continuous bottom-up optimization. By analyzing and simulating the fuzzy control principle, the following conclusions are obtained.

1) The addition of fuzzy logic control in primary control results in smoother sinusoidal voltage output and reduces the THD, indicating the proposed fuzzy logic has a positive impact on improving electric energy. 2) The introduction of fuzzy logic control in secondary control reduces frequency fluctuation of the microgrid's output voltage when the load of the microgrid changes. This enhances the microgrid's anti-interference ability and improves power quality. The improvement of the control of the microgrid will improve the utilization rate of various clean energy sources and promote the transformation of energy structure.

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基于采用模糊逻辑分层控制的交流微电网的频率调节

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摘要: 交流 (alternating current, AC) 微电网是一种集成可再生能源、电力变换器、控制器和负载的系统。分层控制可以管理微电网的频率, 防止系统失衡和崩溃。现有的频率控制方法使用传统的比例积分 (proportion integration, PI) 控制器, 无法实时调整 PI 参数以应对系统的状态变化。由模糊逻辑驱动的分层控制可以实时调整 PI 参数, 该方法采用两层控制结构。一层控制采用下垂控制调整功率分配, 模糊逻辑用于一层控制的电压环路。二层控制用于弥补下垂控制造成的频率偏差, 在二层控制中使用模糊逻辑, 以处理负载扰动引起的频率动态变化。在 Matlab/Simulink 中对所提出的方法进行仿真, 在一层控制中, 所提出的方法将输出电压两个周期的总谐波失真率 (total harmonic distortion, THD) 从 4.19% 降低到 3.89%; 在二层控制中, 当负载增加和减少时, 所提出的方法分别将系统的频率波动降低约 0.03 Hz 和 0.04 Hz。结果表明, 所提出的方法对 AC 微电网的频率维持和电压控制有较好的效果。

关键词: 模糊逻辑; 分层控制; 频率调节; 下垂控制; 交流 (AC) 微电网