Frequency coordinated control strategy based on sliding mode method for a microgrid with hybrid energy storage system

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Abstract
Frequency stability is important for microgrid with renewable energy. However, the deterioration of frequency and the increased energy storage equipment are caused by source-load uncertainty. Therefore, a frequency coordinated control strategy based on sliding mode method for a microgrid with hybrid energy storage system (HESS) is proposed. First of all, the detailed frequency regulation is designed, which divides deviation of frequency and area control error into different components as power reference value of different power supply. Secondly, the power threshold of HESS, which is consisted of ultra-capacitor and battery, is set by designed fuzzy controller to reduce reserve power of HESS and avoid unreasonable power output. Thirdly, a load frequency control model with HESS is built and a sliding mode control is designed by using the detailed frequency regulation. Finally, the effectiveness of the proposed frequency coordinated control strategy is verified through comparison of different cases.

1 | INTRODUCTION
The large-scale consumption of renewable energy is promoted by rapid development of microgrid, however, power balance and frequency stability of microgrid are broken due to unpredictable random changes of renewable energy [1–3]. The microgrid stability and the demand side normal operation are affected by the fluctuated frequency. Therefore, it is important to suppress frequency deterioration caused by uncertainties of source-load.

Load frequency control (LFC) is one of the important measures to keep power system to be stable. The purpose of LFC is to maintain system frequency at the nominal value and minimize tie-line power between different areas [4, 5]. Many researches have been carried out to optimize LFC of power system. Some advanced control algorithms are applied to LFC design to solve the problem of source-load uncertainty. In ref. [6], the proportional-integral-differential parameters of LFC are adjusted by internal model control to improve the damping of power system. In ref. [7], an adaptive control is designed at the sub-system level to guarantee that the fluctuations on the load frequency converge to a range in multi-area power system. In power system operation and control, fuzzy logic can handle problems with the capability in solving system uncertainty and non-linear or un-modelled systems [8]. In ref. [9], area control error (ACE) and its rate of change are inputs of the designed fuzzy logic control (FLC), which can provide the optimal regulation instruction for frequency recovery when disturbance occurs. A self-adaptive virtual inertia control-based fuzzy logic is proposed to improve frequency stability of microgrid. Virtual inertia constant is provided by taking frequency deviations and real power changes of renewable energy sources as inputs to FLC [10]. In ref. [11], an adaptive and fuzzy proportional-integral (PI) controller is designed for frequency regulation of isolated microgrid. The parameters of PI controller are optimized by taking the frequency change and the frequency change rate as the input of FLC. In ref. [12], a robust LFC design using equivalent input disturbance is proposed to improve frequency stability of power system. Sliding mode method is widely used in LFC design as a strong robust theory. In ref. [13], a sliding mode LFC strategy is proposed to assure the stability of multi-area power system with mismatched uncertainties by selecting the appropriate switching surface. In ref. [14], an improved sliding mode control (SMC) is designed based on a new sliding mode variable, which is combined with adaptive dynamic programming to form a new LFC method. The method has
a favourable performance for frequency regulation under load disturbances and parameter uncertainties. A sliding mode LFC is designed to reduce overshoot/undershoot magnitude of frequency deviation for multi-area power system with matching and unmatched uncertainties [15, 16]. In ref. [17], a terminal SMC for robust LFC is designed for islanded microgrid so that frequency oscillation originated from intermittent nature of renewable energy resources and load variations is damped appropriately. In ref. [18], a robust SMC strategy based on adaptive event-triggered mechanism is proposed against frequency deviation caused by power unbalance for interconnected microgrids. The above-mentioned literatures mainly carried out research from FLC and SMC to optimize performance of LFC. The frequency deviation caused by uncertainties of source-load in microgrid or multi-area power system with renewable energy is effectively suppressed by using various control methods to optimize frequency regulation ability of diesel generator or traditional generator. However, the proportion of renewable energy in microgrid continues to increase, which requires microgrids to have faster frequency response speed and greater frequency regulation capacity. The stricter frequency regulation requirements of microgrids cannot be met by a single type of power supply.

Compared with traditional generators, energy storage systems with faster dynamic response capabilities are introduced into LFC, such as, battery [19], ultra-capacitor (UC) [20, 21], flywheel energy storage [22], pumped storage [23]. Transient power fluctuations from seconds to minutes can be handled by UC with higher power density, battery with higher energy density can operate for a longer period of time [24, 25]. In ref. [26], frequency deviation in power system is reduced by the wind energy conversion system with battery energy storage. In ref. [27], frequency support is provided by the doubly fed inductive generator with energy storage system and a second frequency drop is avoided. In these literatures, the energy storage system is mainly used to smooth the output power of renewable energy supplies. The frequency deterioration caused by the source side is suppressed. In ref. [28], a hybrid energy storage system (HESS) consisting of battery and UC is studied for frequency regulation. By comparing the performance of different types of energy storage technology on frequency regulation under different source-load fluctuations, the positive role of energy storage system in LFC is reflected. In ref. [29], a secondary frequency regulation strategy is proposed by considering automatic generation control and state of charge (SOC) of battery. The transient and steady performances of frequency are improved and battery storage can be better. Electric vehicles (EV) are often regarded as an energy storage system. In ref. [30], a two-level hierarchical supervisory control system is proposed for integrated with EV participating in frequency regulation. A FLC with two inputs (frequency deviation and current SOC level) and one output (control signal to adjust EV output power) is designed at the lower level. In ref. [31], the suppression of frequency deterioration in microgrid is realized by combining a small battery with a sophisticated robust control algorithm. In ref. [32], a HESS is applied to improve the performance of LFC by combining the state feedback robust control theory with linear matrix inequality theory. These literatures show that coordinated strategy of the HESS and traditional generator has a better suppression effect on the frequency deterioration caused by the source-load uncertainties. However, these literatures focus on the following aspects: The output of renewable energy units is smoothed by energy storage system, LFC performance is optimized by using advanced algorithms, the combination of different energy storage technologies and the impact on LFC performance is analysed.

Based on the above analysis, the frequency coordinated control strategy for microgrid based on sliding mode method for a microgrid with HESS is proposed. The output power reference value of the power supply participating in frequency regulation is processed in detail through the proposed coordinated control strategy. The power change threshold of HESS is connected with frequency deviation and ACE deviation through the logic controller, which makes the power change of HESS more reasonable in the process of primary and secondary frequency adjustment. The designed SMC is based on the proposed frequency coordinated control strategy, which is beneficial to realize the robustness of the microgrid with HESS. The main contributions of this paper are stated as follows. First of all, in order to promote coordinated operation capability of diesel generator and HESS, the detailed frequency regulation is designed to reasonably determine the reference power of different units during operation. Second, based on the detailed frequency regulation, the LFC model with energy storage system is established to satisfy the proposed coordinated strategy. The SMC based on the LFC model is designed to suppress the source-load uncertainties, optimize amplitude and response speed of output power of different power units. Third, the threshold of output power of HESS is set by designed fuzzy controller to reasonably arrange the reserve power for frequency regulation of HESS. Finally, four cases based on different wind energy permeability are designed to verify the effectiveness of the proposed frequency coordinated control strategy.

The remaining of paper is organized as follows. Section 2 introduces the interconnected microgrid system with HESS. The frequency coordinated control strategy is proposed in Section 3. And in Section 4, a new LFC model is established and SMC is designed based on the proposed frequency coordinated control strategy. Four cases are designed in Section 5 to verify the effectiveness of the proposed frequency coordinated control strategy. Finally, the conclusion is given in Section 6.

## 2 INTERCONNECTED MICROGRID SYSTEM WITH HYBRID ENERGY STORAGE SYSTEM

The proposed frequency coordinated control strategy is applied to interconnected microgrid which contains diesel generator, wind turbine generator (WTG), battery, UC and random load. The power balance of interconnected microgrid is described as follows,

\[ \Delta P_{Li} = \Delta P_{di} + \Delta P_{bi} + \Delta P_{UCi} + \Delta P_{WT} - \Delta P_{ri}. \]  (1)
where $\Delta P_{ij}$ is load variation, $\Delta P_{di}$, $\Delta P_{bi}$, $\Delta P_{UCi}$, $\Delta P_{Wi}$ are output power variation of diesel generator, battery, UC and WTG in area $i$, respectively. $\Delta P_{ij}$ is variation of tie-line power between area $i$ and area $j$.

Rate of change of ACE can be described as

$$\Delta \text{ACE} = \Delta P_{ij} + \phi \Delta f. \quad (2)$$

where $\phi$ is frequency deviation factor, $\Delta f$ is rate of change of frequency.

The diesel generator is an important part of LFC, which undertakes the main frequency regulation of microgrid. The transfer function of diesel generator can be obtained from refs. [3, 6, 33].

The HESS composed of battery and UC has better dynamic response performance. UC is used to respond to frequency fluctuations caused by instantaneous power imbalance since UC has fast response time, high power density and larger cycle life. Battery is used to respond to ACE of interconnected microgrid since battery has high energy density which can provide longer energy output. Battery and UC are represented by first-order lag model, and their performance differences are reflected by different parameter settings. The transfer function of HESS has been described in ref. [3, 28, 31, 34].

Wind energy is a clean energy with random fluctuations, and it is also one of the important factors that cause frequency deviations in microgrids. The WTG model can refer to the related content in refs. [2, 35].

### 3 PROPOSED FREQUENCY COORDINATED CONTROL STRATEGY

The inertia of microgrid is reduced due to the penetration of renewable energy. Diesel generator cannot fully meet frequency regulation of microgrid with renewable energy due to the constraints of ramp rate, maximum output power and operation dead zone. Energy storage system is introduced to assist diesel generator in frequency regulation. The experimental result in ref. [36] showed that the response speed of battery is 60 times that of traditional generator. However, battery cannot frequently respond to instantaneous frequency fluctuation because of its limited times of charge and discharge, and UC makes up for this disadvantage. Therefore, the frequency coordinated control strategy is proposed based on interconnected microgrid composed of diesel generator, HESS and WTG. The proposed frequency coordinated control strategy is divided into three parts, as shown in Figure 1. Part 1 is the detailed frequency regulation of interconnected microgrid frequency. Part 2 is setting of power threshold by fuzzy controller. Part 3 is SMC design.
component of $\Delta f$ and $\Delta \text{ACE}$. Part 2, the power threshold of HESS is determined by the fuzzy controller. Part 3, designed SMC based on the LFC model and the detailed frequency regulation is used for diesel generator to compensate source-load uncertainties. In Figure 1, $P_{\text{UC,fuzzy}}$, $P_{\text{b,fuzzy}}$ are the power threshold of HESS, which are given by the fuzzy controller. $u(t)$ is the compensation power of diesel generator, which comes from the control rate of SMC.

### 3.1 Detailed frequency regulation for a microgrid

The rate of change of frequency as the important target of primary frequency adjustment needs to be responded quickly by power supplies to compensate for the imbalance of instantaneous power of microgrid. $\Delta f$ is divided into high and low frequency components. UC is designed to respond to the high frequency components of $\Delta f$ due to its fast response capability and more cycle times. The low frequency component of $\Delta f$ is used as compensation for the droop control of diesel generator governor. Tie-line power variation and secondary frequency regulation of interconnected microgrid are reflected by $\text{ACE}$. Although the response requirement of $\text{ACE}$ is lower than that of frequency deviation, it cannot be satisfied only by regulation of diesel generator. $\Delta \text{ACE}$ is divided into high and low frequency components. Battery is designed to respond to the high frequency components of $\Delta \text{ACE}$ because of its fast response than the diesel generator. The low frequency component of $\Delta \text{ACE}$ is used as reference value for the secondary frequency regulation of diesel generator. Through the above decomposition of $\Delta f$ and $\Delta \text{ACE}$, the advantages of diesel generator and HESS are reflected, and frequency regulation pressure of diesel generator is also relieved.

The detailed frequency regulation for a microgrid is implemented when the SOC of HESS is within a reasonable range. The SOC of HESS is beyond the reasonable range of its operation, which causes the frequency regulation of a microgrid to be realized only by diesel generator using SMC. Of course, it is also a reasonable scenario that the SOC of battery is within a reasonable range but the SOC of UC not. In this scenario, other control strategy have been adopted that battery responds to the high frequency component of $\Delta f$, and UC no longer responds to the high frequency component of $\Delta f$. The primary frequency adjustment is realized by diesel generator.

### 3.2 Setting of power threshold by fuzzy controller

The high frequency component of $\Delta f$ and $\Delta \text{ACE}$ are responded by UC and battery, respectively. When the source-load fluctuates greatly, the instruction of high-power charging and discharging are given to the HESS to restrain frequency deterioration and restore frequency stability as soon as possible. However, large power input and output of UC and battery due to the different regulation instruction, which results in aggravating the power imbalance of microgrid. The fuzzy controller is designed to provide power threshold for HESS based on $\Delta f$ and $\Delta \text{ACE}$. According to the different amplitude range of $\Delta f$ and $\Delta \text{ACE}$, the fuzzy rule determines different power thresholds, and the power variation of HESS can be described as follows,

$$
P_{\text{UC}} = \min(P_{\text{UC,max}}, P_{\text{UC,fuzzy}}),
$$

$$
P_{\text{b}} = \min(P_{\text{b,max}}, P_{\text{b,fuzzy}}),
$$

$$
\text{SOC}_{\text{b, min}} \leq \text{SOC}_{\text{b}} \leq \text{SOC}_{\text{b, max}},
$$

$$
\text{SOC}_{\text{UC, min}} \leq \text{SOC}_{\text{UC}} \leq \text{SOC}_{\text{UC, max}},
$$

(3)

where $P_{\text{UC,max}}$ and $P_{\text{b,max}}$ are the maximum variation power of HESS, $\text{SOC}_{\text{UC, min}}, \text{SOC}_{\text{UC, max}}$, $\text{SOC}_{\text{b, min}}, \text{SOC}_{\text{b, max}}$ are the variation range of SOC of HESS, $\text{SOC}_{\text{UC}}$, $\text{SOC}_{\text{b}}$ are SOC states of HESS, respectively. The designed fuzzy controller and fuzzy rules are shown in Figure 2.

The power change of HESS limited by frequency adjustment instruction given by central controller and threshold value given by the fuzzy controller, which avoids frequency deterioration of microgrid caused by unreasonable adjustment instruction. At the same time, the setting of power threshold provides the possibility to reduce reserve capacity of HESS for frequency regulation.

### 4 NEW LOAD FREQUENCY CONTROL MODEL BUILD AND SLIDING MODE CONTROL DESIGN

Sliding mode method is a kind of nonlinear robust control, which is insensitive to external disturbance. Based on the detailed frequency regulation of microgrid, sliding mode method is used to suppress the uncertain disturbance of WTG and the uncertain fluctuation of load demand.

In Figure 3, based on the proposed coordinated strategy, the new LFC model is built with HESS. The state vector of interconnected microgrid area $i$ can be expressed as follows,

$$
x(t) = [\Delta f_i(t) \: \Delta P_{\text{di}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta P_{\text{ui}}(t) \: \Delta E_i(t) \: \Delta \text{ACE}_{\text{li}}(t) \: \Delta P_{\text{ui}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta E_i(t) \: \Delta P_{\text{di}}(t) \: \Delta E_i(t) \: \Delta P_{\text{ui}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta E_i(t) \: \Delta P_{\text{di}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta E_i(t) \: \Delta P_{\text{ui}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta E_i(t) \: \Delta P_{\text{di}}(t) \: \Delta P_{\text{gi}}(t) \: \Delta E_i(t)]^T.
$$

(4)
where $\Delta f_i(t)$ is rate of change of frequency, $\Delta P_{bi}(t)$, $\Delta P_{gi}(t)$, $\Delta P_{bi}(t), \Delta P_{gi}(t)$ are output power variation of diesel generator, diesel generator governor, battery and UC, respectively. $\Delta E_i(t)$ is increment of integral controller, $\Delta P_j(t)$ is low frequency component for diesel generator, $\Delta ACE_i(t)$ is rate of change of ACE, $\Delta ACE_{ij}(t)$ is low frequency component of $\Delta ACE_i(t), \Delta P_j(t)$ is variation of tie-line power between area $i$ and area $j$.

In Figure 3, $T_g, T_s, T_p$ are time constant, $K_r$ is system gain. $R$ is governor speed adjustment coefficient, $K_i$ is filter gain, $K_f$ is frequency gain. $T_{i1}$ is tie-line power synchronisation factor. $T_{i2}$ is low frequency filter time constant for battery. $T_{i3}$ is sliding mode surface in area $i$. $K_r$ and $T_p$ are gain and time constant of battery. $K_r$ and $T_p$ are gain and time constant of UC. According to Figure 3, the state equation of microgrid area $i$ is described as follows,

$$\Delta \dot{f}_i(t) = \frac{1}{T_p} \Delta f_i(t) + (\Delta P_{bi}(t) + \Delta P_{gi}(t) + \Delta P_{UC}(t))$$

$$\Delta \dot{P}_{bi}(t) = -\frac{1}{T_i} \Delta P_{bi}(t) + \frac{1}{T_i} \Delta P_{bi}(t) + \Delta P_{bi}(t).$$

$$\Delta \dot{P}_{gi}(t) = -\frac{1}{T_g} \Delta P_{gi}(t) - \frac{1}{R} (\Delta f_i(t) + \Delta E_i(t))$$

$$\Delta \dot{P}_{gi}(t) = -\frac{1}{T_i} \Delta P_{gi}(t) + \frac{1}{T_i} \Delta P_{gi}(t).$$

$$\Delta \dot{E}_i(t) = \Delta ACE_{ij}(t).$$

$$\Delta ACE_{ij}(t) = -\frac{1}{T_{i1}} (\Delta ACE_{ij}(t) - \Delta P_{ij}(t)) + \frac{K_r}{T_{i1}} \Delta f_i(t).$$

$$\Delta \dot{P}_{UC}(t) = -\frac{1}{T_C} \Delta P_{UC}(t) + \frac{K_r}{T_C} (K_i \Delta f_i(t) - \Delta P_{ij}(t)).$$

$$\Delta \dot{P}_{bi}(t) = -\frac{1}{T_b} \Delta P_{bi}(t) + \frac{1}{T_b} (K_i (K_i \Delta f_i(t) + \Delta P_{ij}(t)))$$

$$\Delta P_{ij}(t) = 2\pi T_{LA} (\Delta f_i(t) - \Delta f_j(t)).$$

Equations (5)–(13) can be described as

$$\dot{x}(t) = Ax(t) + Bu(t) + F_W \Delta P_W(t) + F_L \Delta P_L(t).$$

where $A$, $B$, $F_W$, $F_L$ are system matrix, control matrix, WTG matrix and load matrix, respectively.

In order to facilitate the design of SMC, the aggregate source-load uncertainty in area $i$ are defined as

$$U_{Vi}(t) = F_W \Delta P_W(t) + F_L \Delta P_L(t).$$

Equation (14) is expressed as

$$\dot{x}(t) = Ax(t) + Bu(t) + U_{Vi}(t).$$

The following basic assumptions [37–40] are given for the system described in Equation (16).

Assumption 1, $(A, B)$ is fully controllable.

Assumption 2, $\text{rank}[B, U_{Vi}(t)] \neq \text{rank}[B]$, the uncertainty of the system is unmatched.

Assumption 3, the aggregated source-load uncertainty $U_{Vi}(t)$ is bounded, vector norm of $U_{Vi}(t)$ satisfies condition $\|U_{Vi}(t)\| \leq \xi$, $\xi$ is a known constant.

The conventional sliding surface $\tau_i(t)$ is designed as

$$\tau_i(t) = C_{Hi} x_i(t).$$

where $C_{Hi}$ is a constant full rank matrix about area $i$, which is obtained by pole assignment.
When the dynamic trajectory of any point in space reaches the sliding surface, the switching function needs to satisfy the condition \( \tau_i(t) = 0 \) and \( \dot{\tau}_i(t) = 0 \). The equivalent control in area \( i \) is deduced by Equations (16) and (17) as

\[
\nu_{eq}(t) = -(C_{1H} B)^{-1} (C_{1Hr} A \xi_i(t) + C_{1H} U_{H}(t)).
\]

The power exponent approach rate is adopted as follows,

\[
\nu(t) = -k_{1H} \left| \tau_i(t) \right|^2 \alpha_{1H} \arctan(\tau_i(t)).
\]

where \( k_{1H} > 0 \), \( 0 \leq \alpha_{1H} \leq 1 \), \( \arctan(*) \) is arctangent function.

According to Equations (18) and (19), \( \dot{\tau}_i(t) = 0 \), and Assumption 3, the control law of SMC in area \( i \) based on LFC model of interconnected microgrid can be expressed as follows,

\[
\nu_i(t) = -(C_{1H} B)^{-1} \left( C_{1Hr} A \xi_i(t) + C_{1H} \xi \right)
- (C_{1H} B)^{-1} k_{1H} \left| \tau_i(t) \right|^2 \alpha_{1H} \arctan(\tau_i(t)).
\]

When the system Equation (16) satisfies the arrival condition \( \tau_i(t) \dot{\tau}_i(t) < 0 \), the trajectory of the system is keep near the sliding mode surface by control law of SMC.

### 5 | SIMULATION STUDIES

Eight operation modes are designed and four cases are used to analyse superiority of the proposed frequency coordinated control strategy. The parameters of interconnected microgrid are shown in Table 1. The reference power value is selected as 500 MW, the rated power of diesel generator, WTG, battery and UC are 0.6, 0.32, 0.2 and 0.1 p.u., respectively. The average power of load demand is 0.75 p.u.

Operation mode 1, energy storage system is not included in microgrid, and frequency regulation is implemented by PI LFC. HESS is added in operation mode 2, but PI LFC control is still used. Compared to operating mode 2, the detailed frequency regulation is used to provide the reference power of diesel generator and HESS in operation mode 3. Compared with PI LFC in operation mode 4, SMC LFC is used for frequency regulation. The proposed frequency coordinated control strategy is applied to operation mode 5, which increases the power threshold of HESS compared with operation mode 4. In order to verify effectiveness of the proposed strategy with different source-load uncertainties and wind energy permeability, operation mode 6–8 is designed. In operation mode 6, the different uncertainty factor is added to wind speed and load demand. Wind energy permeability of operation mode 6/7/8 is 46%, 55% and 60%, respectively. The configuration of different operation modes is shown in Table 2.

#### 5.1 | Case 1

Operation mode 1–3 is compared in case 1 to verify that the capability of frequency regulation and dynamic response of microgrid are closely related to the participation of energy storage system and the adoption of detailed frequency regulation. Changes in load demand and WTG output power are represented by a continuous step curve. The maximum power shortage of microgrid is 0.14 p.u. at 120 s, and the frequency deviation becomes the largest.

The frequency deviation of microgrid and the variation of tie-line power between microgrids under different operation modes are shown in Figure 4a,b. Output power of diesel generator and HESS under different operation modes are shown in Figure 4c,d.

| Mode | Energy supply | Frequency regulation strategy | Wind energy permeability |
|------|---------------|-----------------------------|--------------------------|
| 1    | Diesel generator, WTG | PI LFC | 46% |
| 2    | Diesel generator, WTG, HESS | PI LFC | 46% |
| 3    | Diesel generator, WTG, HESS | PI LFC, detailed frequency regulation | 46% |
| 4    | Diesel generator, WTG, HESS | SM C LFC, detailed frequency regulation | 46% |
| 5    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 46% |
| 6    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 46%, uncertainty factor change |
| 7    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 55% |
| 8    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 60% |

### TABLE 1 | The parameters of interconnected microgrid

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( K_{pu} \), p.u. | 120 | \( K_{1i}, \) p.u. | 0.25 |
| \( T_{pu}, s \) | 15 | \( T_{1i}, s \) | 0.24 |
| \( T_i, s \) | 0.0728 | \( y, m \) | 14 |
| \( T_{r}, s \) | 0.273 | \( \rho, kg m^{-3} \) | 1.225 |
| \( K_c, p.u. \) | 0.2 | \( f_c, kg m^{-2} \) | 62.993 |
| \( C_{fe} \) | 0.6 | \( R_{fe}, \Omega \) | 0.0039 |
| \( K_{vu} \), p.u. | 0.03 | \( R_{vu}, \Omega \) | 0.0044 |
| \( T_{vu}, sec \) | 0.08 | \( X_{vu}, \Omega \) | 0.0038 |
| \( T_{lu}, s \) | 4 | \( X_{lu}, \Omega \) | 0.0534 |
| \( T_{lf}, s \) | 0.035 | \( k_{1H} \) | 500 |
| \( K_{vu} \), p.u. | 0.15 | \( \alpha_{1H} \) | 0.6 |
| \( K_{vu} \), p.u. | 0.25 | | |

### TABLE 2 | The different operation modes of microgrid

| Mode | Energy supply | Frequency regulation strategy | Wind energy permeability |
|------|---------------|-----------------------------|--------------------------|
| 1    | Diesel generator, WTG | PI LFC | 46% |
| 2    | Diesel generator, WTG, HESS | PI LFC | 46% |
| 3    | Diesel generator, WTG, HESS | PI LFC, detailed frequency regulation | 46% |
| 4    | Diesel generator, WTG, HESS | SM C LFC, detailed frequency regulation | 46% |
| 5    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 46% |
| 6    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 46%, uncertainty factor change |
| 7    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 55% |
| 8    | Diesel generator, WTG, HESS | Frequency coordinated control strategy | 60% |
In Figure 4a, it is found that the amplitude of frequency deviation is the smallest, and the frequency recovery speed is the fastest under operation mode 3. The dynamic response performance of frequency is improved by using the HESS and the detailed frequency regulation. Although the HESS is used in operation mode 2, frequency deterioration is caused by unreasonable frequency regulation. In case of maximum power shortage, compared with the maximum frequency deviation 0.56 Hz in operation mode 2, the frequency deviation of operation mode 1 is 0.5 Hz, and that of operation mode 3 is 0.4 Hz. The variation of tie line power in operation mode 3 is also the smallest from Figure 4b. As shown in Figure 4c,d, compared with operation modes 1 and 2, on the basis of ensuring that frequency change of microgrid is minimalized and power change of diesel generator is not increased, power change of HESS in operation mode 3 is obviously reduced. The detailed frequency control proposed can achieve frequency deviation suppression and reasonably arrange power changes of different power supply systems, which is proved by Case 1.

5.2 | Case 2

In case 2, operation mode 3 and 4 are compared to verify that frequency performance is improved through the application of SMC in LFC. The frequency deviation, the variation of tie-line power between microgrids and output power of diesel generator under different operation modes are shown in Figure 5. The different frequency components of $\Delta f$ and $\Delta$ACE produced by the proposed frequency coordination control strategy in operation mode 4 are shown in Figure 5d.

The frequency deviation of operation mode 4 is maintained in the range of $\pm 0.1$ Hz in Figure 5, which shows that performance of diesel generator is improved by using SMC to provide compensation for governor. Not only amplitude variation is reduced, but also response speed is improved when source-load fluctuation occurs as shown in Figure 5c. Tie-line power of microgrids has not significantly reduced by using SMC in Figure 5b. Figure 5d shows that the rate of change of low-frequency components is significantly lower than that of high-frequency components. The low frequency component is used as power reference value for frequency adjustment of diesel generator, and the high frequency component is used as frequency adjustment power reference value for HESS, which is consistent with the frequency response characteristics of different power supply systems. The low-frequency component accounts for a large proportion of frequency and ACE change rate, diesel generator, as the main frequency adjustment system, realizes stable frequency support of microgrid by responding to low-frequency components.

5.3 | Case 3

The proposed frequency coordinated control strategy is verified in case 3 by compared operation mode 4–5. The frequency deviation of microgrid, the variation of tie-line power between microgrids and output power of HESS under different operation modes are shown in Figure 6.

In Figure 6a,b, it can be seen that the frequency deviation is suppressed within a reasonable range, and the power fluctuation of tie-line is maintained within a small range by adopting the
FIGURE 5  Operation result of mode 3–4. (a) Frequency deviation, (b) tie-line power, (c) output power of diesel generator and (d) high and low frequency component in mode 4

FIGURE 6  Operation result of mode 4–5. (a) Frequency deviation, (b) tie-line power, (c) output power of battery and (d) output power of UC

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proposed frequency coordinated control strategy in operation mode 5. In Figure 6c, it can be clearly found that by using fuzzy controller to set power threshold for the HESS, the power variation amplitude of battery is significantly reduced. The power variation of UC can be divided into two different situations in operation mode 5, as shown in Figure 6d. When the power imbalance of microgrid is serious, the imbalance between supply and demand is timely relieved through greatly changing the power of UC. When the power imbalance of microgrid is slight, the power change of UC is smaller than that of operation mode 4. Through analysis, the frequency and tie-line power variation...
It can be seen from Figure 7a–c that the frequency deviation and the tie-line power of microgrid are kept in a reasonable range under different wind energy permeability and source-load uncertainty by adopting the proposed frequency coordinated control strategy. However, with the increase of uncertain factors, although the frequency deviation is suppressed within a reasonable range, the frequency performance deteriorates.

6 | CONCLUSION

The frequency coordinated control strategy is proposed for interconnected microgrid with HESS based on SMC. Frequency regulation capability and response speed of microgrid are improved by using the detailed frequency regulation. The SMC is designed by using the new LFC model to optimize frequency regulation capability of diesel generator, and the LFC robustness of the microgrid is enhanced to suppress the source-load uncertainty. In addition, the reserve power for frequency regulation of HESS is reasonably reduced though the designed fuzzy controller, which output as the power threshold of HESS. Through eight different operation modes and four different cases, it is verified that the frequency deviation and the tie-line power fluctuation stabilise in a small reasonable range under different wind energy permeability and uncertainty factor. The proposed frequency coordinated control strategy does not include all scenarios that will be improved in future research.

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