1 Introduction

As more distributed renewable generations (DRGs) are included into the power systems, the load frequency control (LFC) is crucial for the stable operation of the systems [1, 2]. The LFC has been widely used in conventional electric power systems, and it can maintain the stability of frequency by the optimal control, proportional integral (PI) control and other methods [3–5].

Due to transmitting remote measurements and control commands, an open communication network usually introduces time delays to the LFC system [6, 7], which will influence the stability of the power system. Some studies have considered the time delay in the LFC. A delay-dependent robust method is proposed for analysis of a proportion integration differentiation (PID)-type LFC scheme considering time delays in [8]. The delay-dependent stability of the LFC scheme is investigated by using Lyaponuv-theory based delay-dependent criterion and linear matrix inequalities techniques in [9]. In [10], the LFC is presented for two area power system based on estimated time delay and packet loss probability using the Markovian approach, and the modelling and PID controller design for LFC together demand side response with time delay is investigated in [11].

Although the studies mentioned above have investigated the multi-area power system with communication delay for LFC, the considered area only contains conventional power generations. However, the microgrid including conventional power generations, energy storage devices and distributed power generations operates more flexibly, and the electric vehicles (EVs) based on vehicle-to-grid technology can also be used as energy storage devices to participate in LFC to reduce costs when they are connected to the grid [12]. When the microgrid operates in the grid-connected state, the sudden changes in load power of the DGs can cause the deviations in both frequency and tie line power, making the whole system lose stability more easily. Therefore, it is necessary to study the LFC scheme of power system including multi-microgrids with communication delay, and design a more robust controller to maintain its stability.
2.2 LFC model of multi-microgrids

A microgrid can operate on the grid-connected state or the isolated state, and the power of microgrids interacts with the main power system through the tie line. A microgrid can be considered as an area, and a multi-area power system consists of a number of similar microgrids. The equivalent LFC model of the $i$th microgrid is shown in Fig. 2.

A MT consists of the governor, the fuel system, and the turbine. Since there are different numbers of EVs in each EV station, the modelling of EVs could be handled by using equivalent EVs with the same as it, only the wind power generation is considered here.

Since there are different numbers of EVs in each EV station, the modelling of EVs could be handled by using equivalent EVs with different inverter capacities. The transfer function model of the EV is shown in Fig. 4. The discharging power is limited within $0-\mu_e$ if the energy of the EV is down to $E_{\text{min}}$, and the charging power is limited within $-\mu_e$ to 0 if the energy of the EV is up to $E_{\text{max}}$.

The state space model of the microgrid can be expressed as

$$\begin{align*}
\dot{x} &= Ax + Bu + Dw \\
y &= cx
\end{align*}$$

where

$$x = \begin{bmatrix} \Delta \delta_i \Delta P_{\text{osc}} \Delta X_{\text{MT}} \Delta P_{\text{PV}} \end{bmatrix}^T, \quad y = [ACE_i]^T$$

$$u = \begin{bmatrix} \Delta u_{\text{MT}} \Delta u_{\text{PV}} \end{bmatrix}^T, \quad w = [\Delta P_D]^T,$$

$$A = \begin{bmatrix}
0 & -\frac{1}{2H_i} & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{T_i} & 0 & 0 \\
-\frac{1}{RT_i} & 0 & 0 & -\frac{1}{T_i} & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{T_{el}} \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}, \quad D = \begin{bmatrix}
-\frac{1}{2H_i} & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}, \quad C = \begin{bmatrix}
B & 0 & 0 & 0 & 0
\end{bmatrix}^T$$

The $i$th area control error of is defined as

$$ACE_i = \beta \Delta \delta_i + \Delta P_{\text{osc}}$$

(2)

The disturbance power of the microgrid can be represented as

$$\Delta P_D = \Delta P_{\text{PV}} - \Delta P_{\text{L}}$$

(3)

3 Design of load frequency controller based on MPC

When the fluctuation of renewable energy is too large or the load is abruptly changed, a robust controller is needed to adjust the active output of each components of the microgrid, so as to maintain the frequency stability in the power system. The principles of the model predictive control are model prediction, rolling optimisation and feedback correction, which are applicable to nonlinear system.

The state space model of the microgrid can be transformed into the transfer function model as follows:

$$Y(s) = T_{yw} W(s)$$

(4)

where

$$Y(s) = [ASE_i(s)]^T, \quad U(s) = [\Delta u_{\text{MT}}(s) \Delta u_{\text{PV}}(s) \Delta u_{\text{PV}}(s)]^T,$$

$$W(s) = [\Delta P_D(s)]^T, \quad T_{yw} C(sI - A)^{-1} B, \quad T_{yw} = C(sI - A)^{-1} D.$$
The controlled auto-regressive integrated moving-average (CARIMA) model can be used as the predictive model in the model predictive control algorithm. By using a zero-order hold, the CARIMA model can be obtained from (4) as follows:

\[
A(z^{-1})y(t) = B(z^{-1})u(t-1) + D(z^{-1})w(t) + \xi(t)/\Delta \tag{5}
\]

where \(y(t)\) and \(u(t-1)\) are the output and input of the controller, respectively. The difference operator \(\Delta = 1 - z^{-1} \), and \(A(z^{-1})\), \(B(z^{-1})\) and \(D(z^{-1})\) are the polynomial matrices with orders \(n_a\), \(n_b\) and \(n_d\), respectively.

The optimal objective of the system can be represented as follows:

\[
J = \sum_{j=1}^{N_p} \left[ j(t+j) - r(t+j) \right] u_j + \sum_{j=1}^{N_y} ||\Delta y(t+j-1)||_Q^2 \tag{6}
\]

where \(j(t+j)\) is the \(j\)-step optimal output at time \(t\), and \(r(t+j)\) is the \(j\)-step set reference output at time \(t\). \(\Delta y(t+j-1)\) is the \(j\)-step control increment signal at time \(t\). \(N_p\) and \(N_y\) are the prediction time-domain and control time-domain, respectively.

To get the optimal control signals, a standard quadratic programming problem is needed to be solved. Considering the constraints of the components in the microgrid, the problem can be expressed as

\[
\min J \quad \text{s.t.} \quad \Delta U \leq V \tag{7}
\]

where \(\Delta U = [\Delta u(t+1) \Delta u(t+2) \ldots \Delta u(t+N_y-1)]\), and \(\Delta U \leq V\) is a compact form of the constraints. Once the control signal is obtained, only the first row of the vector \(\Delta U\) is carried out as the LFC signals.

### 4 Case studies

The controller designed previously is applied to a multi-area power system for LFC to verify the control effect. The multi-area power system contains three standard microgrids as shown in Fig. 1, and all of them operate in the grid-connected state. The parameters of each component in the microgrid are shown in Table 1 [15]. To simplify the model, it is assumed that the parameters of the components in the three microgrids are the same.

#### 4.1 Case 1: LFC without communication delay

The communication delay is not considered in this case. The fluctuation of the wind power of the three microgrids is shown in Fig. 5, and the fluctuation \(\Delta P_{\text{fl}}=0\) indicates that the wind power is the rated power at this time. The three microgrids are controlled by the MPC-based controller and PI controller, respectively. The load frequency deviations of each microgrid are shown in Fig. 6.

In Fig. 6, it suggests that under the control of MPC-based controller, the load deviation ranges of the system are less than the results with the PI controller, so that the stability of the microgrids and the whole system is better. The area control error of the three microgrids under the MPC-based controller is shown in Fig. 7. Since the wind power fluctuation in the microgrid 3 is relatively intense, the area control error (ACE) of it is also more intense.

#### 4.2 Case 2: LFC with communication delay

There are different constant communication delays of the three microgrids in this case. The time delays for the three are 0.6, 1.2 and 1.8 s, sequentially. The fluctuation of the wind power in the three microgrids is the same as case 1. In Fig. 8, it is shown that the load frequency deviation of the three microgrids can still be controlled within \(\pm 0.05\) Hz for most of the time with MPC-based controller. Comparing with the results of case 1, as the communication delay increases in succession, the load frequency deviation of the microgrid 1–3 is worse than that without delay. It can be concluded that the stability of the microgrid is deteriorated due to the existence of the communication delay.

Also, the frequency deviations of the three microgrids with the PI controller are shown in Fig. 9. During the simulation, the system has been unable to maintain a stable state and oscillate intensely. The area control errors of the three microgrids with the MPC-based controller are shown in Fig. 10. As the communication delay increases from microgrid 1–3, the ACEs fluctuate more and more violently.

#### 4.3 Case 3: LFC with communication delay and combined power disturbance

In addition to the fluctuation of wind power, the loads in the three microgrids have also changed abruptly in this case. At time \(t = 10\) s, \(t = 25\) s and \(t = 40\) s, there are load disturbances \(\Delta P_L = 0.03\) pu in microgrid 1, \(\Delta P_L = -0.05\) pu in microgrid 2 and \(\Delta P_L = -0.04\) pu in microgrid 3. It is shown that the system contains three standard microgrids as shown in Fig. 1.
Fig. 6 Frequency deviations with MPC and PI control
a Frequency deviation of microgrid 1
b Frequency deviation of microgrid 2
c Frequency deviation of microgrid 3

Fig. 7 Area control errors of microgrid 1, microgrid 2 and microgrid 3 with MPC

Fig. 8 Frequency deviations in case 2 and case 1 with MPC
a Frequency deviation of microgrid 1 in case 2 and case 1 with MPC
b Frequency deviation of microgrid 2 in case 2 and case 1 with MPC
c Frequency deviation of microgrid 3 in case 2 and case 1 with MPC

Fig. 9 Frequency deviations of microgrid 1, microgrid 2 and microgrid 3 with PI controller

Fig. 10 Area control errors of microgrid 1, microgrid 2 and microgrid 3 with MPC

Fig. 11 Combined disturbance power for microgrid 1, microgrid 2 and microgrid 3

Fig. 12 Frequency deviations in case 3 and case 1 with MPC
a Frequency deviation of microgrid 1 in case 3 and case 1
b Frequency deviation of microgrid 2 in case 3 and case 1
c Frequency deviation of microgrid 3 in case 3 and case 1
The communication delay has a great influence on the stability of microgrid. The frequency deviation with the PI controller can hardly achieve the desired control effect, so that the system cannot maintain a stable state in this situation.

The area control errors of the three microgrids have significant changes when the load disturbances occur, as shown in Fig. 14, and the controller will adjust the output of the components of the microgrids according to the AC/Es deviation so that the fluctuation of the frequency can quickly restore stability. The output power of the components in different microgrids is shown in Fig. 15.

5 Conclusions

In this paper, the power system model composed of multiple microgrids is built, and the LFC equivalent models for each component of the microgrid are also established. Then the load frequency controller based on the model predictive control algorithm is proposed and designed, and it is applied to the power system with three grid-connected microgrids for simulation. The simulation results show that the controller proposed has a better control effect compared to the traditional PI controller at various disturbances conditions, regardless of taking the communication delay in consideration or not. However, with the increase of the communication delay of the system, the LFC effect of the controller is weakened. Therefore, the length of the communication delay of the microgrid has an important influence on maintaining the stability of the microgrid frequency.

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7 References

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