Secondary control of island microgrid based on distributed multi-agent system under symmetric time delay

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Abstract. Aiming at the voltage and frequency instability caused by the primary control of the island microgrid and the reactive power unevenness caused by the unbalanced circuit impedance, a quadratic control strategy based on the distributed multi-agent system is adopted. This paper is completed to solve the voltage and frequency deviation due to droop control. The application of distributed consistency algorithm under symmetric time delay is analyzed. The theoretical model is built in MATLAB/Simulink to verify the influence of delay on distributed consistency algorithm.

1. Introduction
At present, the microgrid technology is developing rapidly, and the microgrid can operate in both grid-connected and islanded states[1,2,3,4]. The three-layer microgrid control structure is the current mainstream architecture[5]. In the traditional microgrid secondary control structure, a centralized communication structure is generally adopted, and a microgrid central controller (MGCC) is used to provide a reference value of the voltage frequency for the droop control. This approach has a number of disadvantages[6,7]:
(1) The requirements for the stability of the communication system are high. When a certain line fails, it will often lead to the overall flaw of the system;
(2) Strong dependence on the central controller (MGCC);
(3) “Plug and Play” capability is poor, and the use of microgrid is not used;
(4) Only the adjustment of a certain busbar can be completed.
These reasons lead to the fact that the distributed structure gradually replaces the centralized control structure and becomes a more mainstream microgrid control method[9]. In a distributed control structure, each distributed power source can be regarded as a node. Each node only needs to exchange information with its neighboring nodes that have communication links to complete its own stable operation and complete the microgrid. It does not need to rely on the central controller like the centralized control structure. At present, the secondary control of microgrid based on distributed structure has already achieved some results[9,10,11]. In Document 1, The distributed control algorithm is used to control the voltage and frequency in the DC microgrid, and the distributed algorithm problem under the communication delay is considered, which solves the secondary control problem of the DC microgrid. In distributed secondary control, the time delay caused by communication connection is rarely taken into account, but in actual production life, the information transmission between distributed power sources will not be timely, so consider the communication delay. Distributed secondary control is very necessary. In the secondary control of distributed con-
sistency algorithm, the influence of communication delay on secondary control is discussed. Finally, the relevant model was built in the simulation software and the simulation of the secondary control under the influence of delay was completed.

This paper is completed according to the following structure: The second part introduces the distributed structure of the primary control and secondary control of the microgrid. The third part introduces the construction of secondary control, the fourth part discusses the application feasibility of the distributed consistency algorithm in the case of time delay, and the fifth part is the communication structure of the model built on the experimental platform. The sixth part is the simulation results, the seventh part is the conclusion of the paper.

2. Microgrid distributed control structure

Figure 1 is a block diagram of the hierarchical control of the microgrid. It can be seen in the figure that the first-level control, that is, the local control is mainly responsible for stabilizing the inverter voltage; the secondary control mainly completes the correction of the voltage frequency deviation caused by the first-level control. This paper focuses on the study of primary control and secondary control and considered the impact of communication delay on the basis of traditional distributed secondary control. The microgrid model constructed by this is shown in Figure 2.

![Diagram](image)

**Figure 1.** Distributed control structure hierarchy

**Figure 2.** Microgrid secondary control structure with communication delay

The droop control shows the relationship between voltage and reactive power, frequency and active power. The voltage and frequency control is achieved as follows\(^{[12]}\):

\[
\begin{align*}
V_0 &= V_n - nQ \\
\omega_0 &= \omega_n - mP
\end{align*}
\]  

(1)

In the equation, \(V_0\) and \(\omega_0\) are the voltage amplitude and frequency generated by one control; \(V_n\) and \(\omega_n\) are the reference values of the primary control of the voltage frequency, respectively, \(P\) and \(Q\) are the active and reactive power of the distributed power supply; \(m\) and \(n\) respectively The droop control coefficient corresponding to active and reactive power.

The active power and reactive power are calculated using the instantaneous power theory, and the DC component is used here. The DC component can be obtained by filtering the AC component of the first-order low-pass filter. The formula is as follows\(^{[13]}\):
In the equation, $\omega_c$ is the cutoff frequency, and $v_{od}i_{od}$ and $v_{qq}i_{qq}$ are the d-axis and q-axis components of the distributed power supply output voltage and output current, respectively.

The resistance between the inverters has a certain influence on the droop control. If it is directly applied to the distributed control of the microgrid, it affects the stability of the system and the equalization of the power. The introduction of a virtual impedance loop in the line can attenuate the power coupling problem caused by the resistive load. The feedback of the voltage can solve the problem of reactive power unevenness caused by the impedance imbalance of the circuit, thereby improving system performance. The virtual impedance loop is designed as follows

$$
\begin{align*}
P &= \frac{\omega_c}{s + \omega_c} (v_{od}i_{od} + v_{qq}i_{qq}) \\
Q &= \frac{\omega_c}{s + \omega_c} (v_{qq}i_{od} - v_{od}i_{qq})
\end{align*}
$$

In the equation, $\omega_c$ is the cutoff frequency, and $v_{od}i_{od}$ and $v_{qq}i_{qq}$ are the d-axis and q-axis components of the distributed power supply output voltage and output current, respectively.

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$$
\begin{align*}
v_{Vd} &= R_v i_{od}^+ - \omega L_v i_{od}^+ \\
v_{Vq} &= R_v i_{od}^+ + \omega L_v i_{od}^+
\end{align*}
$$

In the equation, $v_{Vd}v_{Vq}$ is the output voltage of the virtual impedance loop, $R_v$ and $L_v$ are the virtual resistor and the virtual inductor respectively. The “+$” sign of the superscript represents the positive sequence component, and the negative sequence current passes through the virtual resistor, resulting in voltage imbalance, so do not join when calculating. In order to reduce the error caused by the uncertainty interference, the inner loop control uses robust control to enhance the stability of the system. The overall control block diagram of the system is shown in Figure 3.

Figure 3. Microgrid primary/secondary control structure

3. Distributed cooperative secondary control

The traditional centralized control structure is shown in Figure 4(a). This control method has a high dependence on the central controller. Therefore, consider the distributed cooperative control structure, as shown in the distributed structure shown in Figure 4(b), distributed power supplies communicate with each other, simplifying the complexity of the organization and reducing communication requirements.
3.1 Voltage controller design

The droop controller is constructed according to the above formula. In the dq coordinate system, the amplitude of the output voltage is:

$$v_{o, mag} = \sqrt{v_{odi}^2 + v_{oqi}^2}$$

$$v_{odi} = 0$$

So the formula for first control can be modified to:

$$v_{odi}' = V_{ril} - n_i q_i$$

$$v_{oqi}' = 0$$

In the formula, $v_{odi}'$ and $v_{oqi}'$ are the d-axis component and the q-axis component of the output voltage, and the subscript $i$ represents the $i$-th distributed generation unit. It can be seen from this that the control purpose of the secondary control is to make $v_{odi}$ tend to $v_{odi}'$, so that the frequency $\omega_i$ tends to $\omega_{ref}$.

Since the voltage and current controller is in a state of dynamic balance, the above equation can be differentiated:

$$v_{odi}' = \dot{V}_{ril} - \dot{n}_i q_i = u_{vi}$$

This process is called input-output feedback linearization, which can transform the voltage synchronization problem of $N$ distributed power supplies into a first-order linear multi-agent synchronization tracking problem:

$$v_{odi} = u_{vi}, \ i = 1, 2, 3 \cdots N$$

The distributed power source DG in the microgrid is regarded as the target node. According to the knowledge of the graph theory, a directed graph can be used instead of the communication relationship between them. A leader node is set in the microgrid. This node provides the reference voltage and the reference frequency. Only a limited number of target nodes can receive the information of the reference node, and other nodes update the voltage and frequency through the communication connection. $u_{vi}$ can be rewritten as:

$$u_{vi} = -c_v e_{vi} = -c_v \left( \sum_{j \in M_j} a_{ij} (v_{odi} - v_{odi}) + g_t (v_{odi} - v_{ref}) \right)$$

where in the formula, $c_v$ is the control gain added to enhance the response speed of the system, $M_j$ repre-
sents the set of adjacent nodes of the target node i, and the relationship between the nodes is constructed into a matrix, which is called adjacency. The matrix $\mathbf{A}$, in the adjacency matrix, the element $a_{ij}$ represents the relationship between the nodes. If $a_{ij}>0$, it means that information is sent from node j to node i. When $a_{ij}=0$, it means that there is no relationship between them. The connection on the information. $g_{i}$ is a gain coefficient. When $g_{i}=1$, it indicates that node i can receive the voltage reference signal sent by the leader node. If the signal cannot be received, $g_{i}=0$.

According to the proof in Document 5, the voltage reference value input to the droop controller is:

$$V_{i} = \int (u_{q} + n_{i} \dot{Q}_{i})dt$$  \hspace{1cm} (9)

In the formula, $\dot{Q}$ is calculated as follows:

$$\dot{Q}_{i} = -\omega_{c}Q_{i} + \omega_{c}(v_{oqi}i_{odi} - v_{odi}i_{oqi})$$  \hspace{1cm} (10)

$\omega_{c}$ is the cutoff frequency of the low pass filter.

The specific structure diagram of voltage secondary control is shown in Figure 5.

3.2 Frequency quadratic controller design

The role of the frequency secondary controller is to cause the angular frequency $\omega_{i}$ of the distributed power source to tend to a given frequency reference value $\omega_{ref}$. According to the definition of droop control:

$$\omega_{i} = \omega_{ni} - m_{i}P_{i}$$  \hspace{1cm} (11)

Analogous to the design of the voltage quadratic controller, the equation can be differentiated to obtain the equation for frequency dynamic transformation:

$$\dot{\omega}_{i} = \dot{\omega}_{ni} - m_{i}\dot{P}_{i} = u_{\omega i} i = 1,2,3,\ldots,N$$  \hspace{1cm} (12)

For $u_{\omega i}$, the frequency quadratic controller can be designed as follows:

$$u_{\omega i} = -c_{\omega} * e_{\omega i} = -c_{\omega} \left( \sum_{j \in M} a_{ij}(\omega_{i} - \omega_{j}) + g_{i}(\omega_{i} - \omega_{ref}) \right)$$  \hspace{1cm} (13)

In the equation, $c_{\omega}$ is the control gain added to enhance the response speed of the system. Combining the above two modes, you can get the frequency input of the secondary control:

$$\omega_{i} = \int (u_{\omega i} + m_{i}\dot{P}_{i}) dt$$  \hspace{1cm} (14)

A slight difference from the voltage secondary control is that the frequency secondary control needs to achieve the equalization of the active power, that is, to achieve:

$$m_{1}P_{1} = m_{2}P_{2} = m_{3}P_{3} = \ldots = m_{i}P_{i} i = 1,2,3,\ldots,N$$  \hspace{1cm} (15)

To maintain the balance of active power, the active power can be calculated as an input according to the idea of designing the voltage frequency controller.
\[ m_i \dot{P}_i = u_{pi} \quad (16) \]
\[ u_{pi} = -c_p \cdot e_{pi} - c_p \left( \sum_{j \in M_i} a_{ij} \left( m_i P_i - m_j P_j \right) \right) \quad (17) \]

Since the active power is not the input of the droop control, there is no intervention of the active power reference value in the calculation, and there is no gain term. Based on the above derivation, the design of the frequency secondary controller can be written as:

\[ \omega_i = \int (u_{ad} + u_{pi}) \, dt \quad (18) \]

The frequency control structure is shown in Figure 6.

4. Secondary control in case of delay

The traditional distributed consistency control algorithm is an ideal situation without considering the delay situation, but in the actual microgrid, communication delay always occurs inevitably. When considering the transmission delay, whether the existing distributed control algorithm can effectively complete the control of voltage and frequency is still a problem to be solved. Here, innovatively based on the traditional control algorithm, consider the transmission delay problem caused by problems such as data transmission and data processing. The structure of the continuity consistency algorithm is as follows:

\[ \dot{x}_i(t) = -\sum_{j \in N_i} a_{ij} \left( x_j(t) - x_i(t) \right) \quad (19) \]

In the formula, \( N_i \) represents the adjacent agent, and \( a_{ij} \) represents the item in the adjacency matrix. When the two nodes are not connected, \( a_{ij} = 0 \), otherwise it is the weight of the corresponding connection edge. Here, the default is 1. The structural formula of the consistency algorithm can also be written as follows:

\[ \dot{x} = -L \cdot x \quad (20) \]

In the formula, \( L \) is the Laplace matrix of the agent corresponding to the directed graph, \( x = [x_1, x_2, \cdots x_n] \).

In actual calculations, for various reasons, the transmission between signals does not always arrive in real time, they often need to delay after a period of time to reach the destination, so consider the time delay in the secondary control of the distributed microgrid. It is very important. In this paper, considering the secondary control under transmission delay, a fixed time delay is added to simulate the transmission delay in the actual system based on the traditional distributed consistency algorithm. The algorithm structure at this time is as follows:

\[ \dot{x}_i(t) = -\sum_{j \in N_i} a_{ij} \left( x_j \left( t - \tau_{ij} \right) - x_i(t - \tau_{ij}) \right) \quad (21) \]

In the equation, \( \tau_{ij} \) is the transmission delay of the simulation, where a fixed time is taken as the value of this item. For multi-agents, the system ultimately needs to achieve consistency, and it needs to meet certain conditions. When the system has time delay, the maximum time delay it can bear:

\[ \tau_{max} = \frac{\pi}{2\lambda_n} \quad (22) \]

In the formula, \( \lambda_n \) is the maximum eigenvalue of the Laplace matrix corresponding to the multi-agent system. When the new transmission delay satisfies \( \tau \leq \tau_{max} \), the system can be operated in a steady state.

5. Distributed cooperative control communication structure

In the distributed topology, we choose each distributed unit to communicate only with its neighbors, specifying a specific node to receive reference information from the leading node. In this way, not only the communication connection is reduced, but also the communication burden caused by a large amount of complicated information exchange can be alleviated, and the information of each distributed node in the
micro grid is included. In the process of simulation, we choose an island microgrid with four nodes. The topology of the microgrid is:

![Image of microgrid topology]

**Figure 7. Frequency secondary controller block diagram**

The adjacency matrix of the topology can be derived:

\[
A = \begin{bmatrix}
0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]  
(23)

The Laplace matrix of the multi-agent is:

\[
L(G) = \Delta(G) - A(G) = \begin{bmatrix}
0 & 0 & 0 \\
-1 & 1 & 0 \\
0 & -1 & 1 \\
0 & 0 & -1
\end{bmatrix}
\]  
(24)

The maximum eigenvalue corresponding to this Laplace matrix is \(\lambda_{\text{max}} = 1\). The maximum value of the delay obtained by calculation is\(^{(15)}\):

\[
\tau_{\text{max}} = \frac{\pi}{2\lambda_{\text{max}}} = 1.57
\]  
(25)

The simulation of the distributed multi-agent system is carried out with a delay of 0.5 seconds, and compared with the distributed multi-agent system without adding time delay, and the influence of the analysis delay on the secondary control of the distributed consistency algorithm is analyzed.

### 6. Simulation results

In order to verify the effect of delay on the distributed consistency algorithm, the model shown in Fig.2 is built in Matlab/Simulink. The grid operating voltage and frequency are set to 380V and 50Hz, and \(c_v\), \(c_\omega\), and \(c_p\) are set to 400. The simulation parameters are shown in Table 1. The microgrid operates in an island operation state. When there is no time delay in the transmission of voltage and frequency, the microgrid gradually enters a steady state after a period of time, and the voltage and frequency are basically stabilized at a preset value. When the delay link is added, there is some fluctuation in the voltage and frequency at this time, but eventually it can tend to set the value. As shown in the figure, after adding a time delay of 0.5 seconds, after applying the algorithm in this article, the voltage has stabilized before 0.5 seconds, and can still remain stable after a slight fluctuation at 0.5 seconds. As for the frequency, it was basically stable before 0.5 seconds, but there was still a certain degree of volatility. When the 0.5 second time delay appeared, it was obvious that the fluctuations were more severe and it could eventually approach a stable state. It shows that the method in this paper has a good regulation effect on island microgrids with time delay.
Table 1. System parameters used for testing

| Parameter | $v_{dc}$ | $m$ | $n$ | $V_n$ | $\omega_n$ | $R_f$ | $C_f$ |
|-----------|---------|-----|-----|-------|------------|-------|-------|
| Value     | 800V    | $9.4 \times 10^{-5}$ | $1.3 \times 10^{-3}$ | 311V   | 31 rad/s   | 1Ω    | 600μF |

| Parameter | $L_f$ | $L_c$ | $k_{pu}$ | $k_{pi}$ | $k_{ir}$ | $k_{ii}$ |
|-----------|-------|-------|----------|----------|----------|----------|
| Value     | 0.2mH | 10mH  | 0.1      | 420      | 15       | 20000    |

7. Conclusion
In the quadratic control of the island microgrid based on the distributed consistency algorithm, the traditional consistency algorithm can solve the voltage and frequency deviation caused by the droop control, but it does not consider the impact due to the transmission time delay. Based on this, the paper considers the influence of delay and adds a fixed time delay to the control algorithm to simulate the delay phenomenon under actual conditions. The related model is built in Matlab/Simulink. The experimental results show that the fixed time delay does not affect the application of distributed consistency algorithm in quadratic control. When the fixed delay value is not greater than the calculated maximum At time lag, the system can still correct the deviation due to droop control.

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