Research on the Influence of Communication Time-Delay on Multi-agent System Based Distributed Energy Dispatching Control Consensus

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Abstract. Multi-agent based distributed control methods are widely applied in distributed energy dispatching control. However, the control processes are highly dependent on the information interaction among the distributed generation units through the communication network. The communication time-delay would affect the performance and stability of the multi-agent based distributed energy dispatching control system. To investigate the effect of communication time-delay on the dispatching control, the incremental cost rate in the economic dispatch model is adopted as consensus variables of multi-agent system, and a multi-agent system with communication time-delay based distributed energy dispatching control consensus algorithm is proposed. Moreover, two cases simulations are implemented and the effects of the time-delay on the consensus convergence are analyzed. This work provides a reference for the optimal design of distributed energy dispatching control.

1. Introduction
In the past several years, the distributed energy resource (DER) is in a booming stage with the characteristics of low greenhouse emissions, renewable, environment friendly. However, the uncertainty, intermittency and fluctuation of the distributed generation and the bidirectional power flow in power distribution network would lead to the huge challenges for energy dispatching control in DER [1]. The centralized control method in traditional power grid is hard to meet the needs of flexible and effective control in DER. The multi-agent system (MAS), proposed as an up-and-coming technology with the properties of autonomy, adaptability, coordination and sociality, is used to solve the collaborative optimization problem of distributed system [2, 3]. At the same time, it also represents great potential value and gains increasing attention in power industry. Many research works also show that MAS is one of the best technologies for introducing distributed energy dispatching control in DER [4-7]. In general, MAS is a complex system composed of a number of autonomous agents, where the agents interact between each other, typically by exchanging information through network [8]. Considering a networked MAS in which agents communicate through a communication network, the time-delay is unavoidable because of the finite signal transmission speeds, limited bandwidth of channels, packet losses, and so on. It is known that the time-delay phenomena commonly cause undesirable dynamic behaviors, for instance, it may lead to oscillation, performance degradation and
instability in system [9]. Therefore, it is important to investigate the influence of communication time-delay on MAS. Many researchers have made in-depth relevant research and got considerable progress [10-12].

In this work, the influence of communication time-delay on MAS based distributed energy dispatching control consensus was studied. First, the graph theory of MAS was described. Second, the incremental cost of distributed generation is adopted as the consensus variable, a distributed energy dispatching control consensus algorithm was designed based on the MAS with time-delay. Finally, the simulations with two cases were carried out and the influence of time-delay to consensus was analyzed. The simulation result provided a reference for the time constraint of multi-agent based distributed energy dispatching control with communication time-delay.

2. Graph Theory of MAS

Suppose that there are $n$ agents in a certain MAS (or network). A graph $G = (V, E, A)$ can be used to model the network topology between agents, where $V = \{v_1, v_2, \cdots, v_n\}$ is the set of the vertices (agents), $E = \{e_{ij} = (v_i, v_j)\}$ is the set of the edges, where the edge $e_{ij} = (v_i, v_j) \in E$ means that agent $v_i$ can sent the information to agent $v_j$. $A = [a_{ij}]_{n \times n}$ is a weighted adjacency matrix with nonnegative element. The adjacency element $a_{ij}$ associated with the edge $e_{ij}$ is positive, i.e., $e_{ij} \in E \iff a_{ij} > 0$. Assume $a_{ii} = 0$ for all $i \in \{1, 2, \cdots, n\}$. For an undirected graph, the adjacency matrix $A$ is symmetric. Let $N_i = \{v_j \in V \mid (v_i, v_j) \in E\}$ denote the neighbor set of node $v_i$, and degree of node $v_i$ is defined as $d_i = \sum_{v_j \in N_i} a_{ij}$ [13]. Subsequently, the diagonal matrix of graph $G$ can be defined as $D = \text{diag}(d_1, d_2, \cdots, d_n)$, and the Laplacian matrix can be defined as $L = D - A$. For an undirected connected graph, $L$ is a symmetric positive semidefinite matrix with all the row sums of $L$ are zero. All the eigenvalues of $L$ are real numbers and can be arranged as $\lambda_0 \leq \lambda_1 \leq \cdots \leq \lambda_n$. Laplacian matrix $L$ reflects the network topological characteristics in MAS, which is one of the crucial natural attributes of the network.

3. Distributed Energy Dispatching Control Consensus Model

The scheme of dispatching control in DER is different from the traditional one which is usually centralized by the control center. Based on the information exchange between the neighboring units through the communication networks, the dispatching control in DER is a distributed and autonomous scheme.

To investigate the optimal output of the generation facilities to meet the demand load with the lowest generation cost, the economic dispatch problem was proposed several years ago. The generation cost in power economic dispatching is usually quantified by quadratic functions or piecewise linear functions. In our work, the cost of each power generation unit is quantified by a quadratic equation with a constant, a single term and a quadratic term. Only the constraints of power generation and load are considered, ignoring the constraints of line capacity and voltage. Based on the above constraints, the generation cost function of each distributed generation unit (DGU) can be described as [14]:

\[ C_i(P_{Gi}) = \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \]  

(1)

where, $P_{Gi}$ and $C_i(P_{Gi})$ represent the active power and the generation cost of DGU $i$, respectively; $\alpha_i$ is the constant; $\beta_i, \gamma_i$ are the coefficients of the first-order term and the second-order term, respectively.

In order to reach the economic optimization, the incremental cost rate of each DGU should be approximately equal, and the constraints of power generation and system balance should be satisfied at
the same time [15, 16]. Denote $\chi_i$ as the incremental cost rate of DGU $i$, then optimization problem can be described as follows:

$$
\begin{align*}
\chi_1 = \chi_2 = \cdots = \chi_n
\chi_i = \frac{\partial C_i (P_{Gi})}{\partial P_{Gi}} = \beta_i + 2 \gamma_i P_{Gi} \\
\sum_{i=1}^{n} P_{Gi} = P_D + P_{\text{loss}} \\
P_{Gi, \text{min}} \leq P_{Gi} \leq P_{Gi, \text{max}}
\end{align*}
$$

(2)

where, $P_{Gi, \text{min}}$ and $P_{Gi, \text{max}}$ are the minimum and maximum active outputs, respectively, $P_D$ is the demand load, and $P_{\text{loss}}$ is the active power transmission loss.

In order to obtain the equal incremental cost rate of each DGU, the MAS based consensus algorithm was introduced. $\chi_i$ could be regarded as the consensus variable of DGU $i$, seen as an agent of MAS. MAS reaches consensus when all consensus variables are equal, therefore the distributed dispatching control obtains the corresponding economic optimization.

Assuming that bi-directional communication can be performed between DGU in DER, and the continuous information interactive could be conducted without interruption, a continuous-time consensus model can be used to describe the MAS. However, in actual operation, the agents usually exchange information at interval, in this case, the discrete-time consensus model should be used to describe the MAS [17]:

$$
\chi_i (k + 1) = \chi_i (k) + T \sum_{j=1}^{n} a_{ij} [\chi_j (k) - \chi_i (k)]
$$

(3)

where, $k$ is iteration number in the optimization process, $T$ is the sampling interval, $a_{ij}$ is the adjacency element of MAS network, $\chi_i$ is the value of agent $i$, $\chi_j$ is the value of agent $j$.

Considering the power balance constraint in equation (2), $\Delta P$ denotes the difference between the sum of demand load $P_D$ and active power transmission loss $P_{\text{loss}}$ and the actual output power of the generators:

$$
\Delta P = P_D + P_{\text{loss}} - \sum_{i=1}^{n} P_{Gi}
$$

(4)

$\Delta P$ controls the global incremental cost rate. When $P_D + P_{\text{loss}}$ is greater than $\sum_{i=1}^{n} P_{Gi}$, the global incremental cost rate will increase; On the contrary, the global incremental cost rate will decrease.

The consensus algorithm in equation (3) is a multi-agent model without considering the communication time-delay. Actually, there exists the communication time-delay caused by signal conversion or transmission among the agents. Considering the global incremental cost rate $\Delta P$, let $\tau_{ij}$ be the communication time-delay between agent $i$ and agent $j$, correspondingly, consensus algorithm in equation (3) can be described as follows:

$$
\chi_i (k + 1) = \chi_i (k) + T \sum_{j=1}^{n} a_{ij} [\chi_j (k - \tau_{ij}) - \chi_i (k - \tau_{ij})] + \varepsilon \Delta P
$$

(5)

where, $\varepsilon$ is the power adjustment coefficient, which is a positive scalar affecting the MAS convergence rate.

The communication time-delay can affect the convergence of the system, and in different network topology, the maximum allowable time-delay for MAS to reach a consensus is different. If the network
topology is undirected and connected, the system can reach consensus when the communication time-delay meets [10]:

$$0 \leq \tau \leq \frac{\pi}{2\lambda_{\text{max}}}$$

(6)

where, $\tau$ is the communication time-delay and $\lambda_{\text{max}}$ is the maximum eigenvalue of the Laplacian matrix $L$.

4. Case Simulation

In order to study the influence of communication time-delay on distributed energy dispatching control consensus, the simulations and analysis are conducted on the IEEE-34 bus test system shown in figure 1. In figure 1, the node $G_i (i=1,2,\ldots,10)$ represents the DGU which could be regarded as an agent, and the remaining nodes represent the loads. The DGUs (i.e. agents) exchange information with each other through the communication link. The parameters $\beta_i$, $\gamma_i$ and initial active power $P_{Gi}(0)$ are listed in table 1 [18]. The demand load is set to 2800 MW, and the active power output range of each generation units is from 150 MW to 500 MW. The transmission loss is set to 5%, and the power adjustment factor $\epsilon$ is set to 0.00003. The iteration step is set to 0.001.

![Figure 1. IEEE-34 bus test system.](image)

Two scheduling cases are designed and the corresponding simulations are conducted in the next section.

| Node | $\beta_i$ | $\gamma_i$ | $P_{Gi}(0)$ |
|------|----------|-----------|-------------|
| $G_1$ | 9.4523   | 0.003256  | 320         |
| $G_2$ | 8.2245   | 0.002457  | 350         |
| $G_3$ | 6.9443   | 0.005365  | 170         |
| $G_4$ | 9.2512   | 0.004682  | 400         |
| $G_5$ | 8.2756   | 0.004256  | 260         |
| $G_6$ | 9.2274   | 0.003987  | 150         |
| $G_7$ | 8.9253   | 0.003124  | 450         |
| $G_8$ | 8.0125   | 0.002475  | 250         |
| $G_9$ | 6.5789   | 0.005425  | 155         |
| $G_{10}$ | 9.0475  | 0.004951  | 165         |
4.1. Case A

According to the communication links shown in figure 1, the network topology is shown in figure 2a and is named $G_{n1}$, moreover its Laplace matrix is written as $L_1$ through the aforementioned graph theory. The maximum eigenvalue of $L_1$ could be calculated $\lambda_{\text{max}} = 4.7817$, and the allowable maximum communication time-delay of the system can be obtained $\tau_{\text{max}} = 0.3285$ through equation (6). Theoretically, when $\tau < \tau_{\text{max}}$, the system can reach consensus, otherwise, the system cannot reach consensus. Based on the consensus algorithm shown in equation (5), the state trajectories of incremental cost rate for each DGU are shown in figure 3.

![Network Topology](image)

**Figure 2.** Network topology.

![State Trajectories](image)

**Figure 3.** State trajectories of incremental cost rate for each DGU.

As shown in figure 3a, the incremental cost rate of each DGU can gradually reach consensus when $\tau = 0.32$ which is less than the allowable maximum communication time-delay (0.3285). In figure 3b, the system is unstable when $\tau = 0.33$ which is greater than 0.3285.

Figure 4 indicates the state trajectories of active power for each DGU and figure 5 provides the variation of $\Delta P$ during the distributed dispatching control optimization process on the condition of consensus.

It can be seen from the figures 3a, 4 and 5 that all the consensus variables in MAS are consistent, meanwhile, constraints of power generation and system power balance are satisfied.

In order to investigate the convergence speed with different time-delay, the lower bound and upper bound of $\tau$ are set 0.001 and 0.320, with interval of 0.001. Figure 6 shows the iteration times under different time-delay $\tau$. 
Figure 4. State trajectories of active power for each DGU.

Figure 5. Variation trajectories of $\Delta P$.

Figure 6. Iteration times under different time-delay $\tau$ with $G_{L1}$.

In figure 6, the time-delay parameter $\tau$ has little impact on the iteration times when $\tau$ varies within the range of $[0.001, 0.268]$, and the average iteration times are about $1.7 \times 10^4$. But the iteration times increase sharply when $\tau$ is over 0.278. So, it is reasonable to say that the time-delay $\tau$ parameter could affect not only the consensus effect but also the consensus convergence speed.

4.2. Case B

Based on $G_{L1}$ in Case A, the adjusted topology network $G_{L2}$ with adding two communication links is shown in figure 2b. Similarly, the adjusted topology network $G_{L3}$ with deleting two communication links is shown in figure 2c.

The maximum eigenvalues of Laplacian matrixes for $G_{L2}$ and $G_{L3}$ can calculated respectively, written as $\tau_{2\text{max}} = 0.2641$ and $\tau_{3\text{max}} = 0.3505$. When $\tau < 0.2641$, the system of $G_{L2}$ could reach the consensus status, and similarly, the system of $G_{L3}$ could reach the consensus when $\tau < 0.3505$.

Figure 7 show the relationship between the iteration times of system convergence consensus and the time-delay parameter $\tau$ with the range of $0.001$-$0.260$ for $G_{L2}$. And figure 8 show the corresponding relationship for $G_{L3}$ with the range of $\tau$ from $0.001$ to $0.340$.

In figure 7, the iteration times increases obviously when $\tau$ exceeds 0.228. When $\tau$ varies within the range of $[0.001, 0.218]$, the average iteration times are $1.01 \times 10^4$; furthermore, the times of iteration does not change significantly. In figure 8, the time-delay parameter $\tau$ has little impact on the iteration times when $\tau$ ranges from 0.001 to 0.290, and the average iteration times are about $2.4 \times 10^4$. The iteration times increases sharply when $\tau$ is over 0.304.
Compared with $G_{L1}$, the connectivity of $G_{L2}$ upgrades, according to the average iteration times in a specific time-delay range, the consensus convergence speed of $G_{L2}$ improved correspondingly. On the contrary, the connectivity of $G_{L3}$ reduces, and the consensus convergence speed becomes slow due to the reduction of communication links. It indicates that the network connectivity has obvious influence on the consensus convergence speed. When considering the network connectivity and the maximum allowable time-delay guaranteeing system consensus convergence, different network connectivity would lead to different maximum allowable time-delay.

5. Conclusion
Taking the incremental cost rate in the economic dispatch as the consensus variables, a distributed energy dispatching control consensus algorithm was designed based on the MAS with time-delay. Through the simulation experiments, the influence of the time-delay parameter on consensus of MAS is investigated. The main conclusions are as follows.

(1) In the MAS based distributed energy dispatching control, the communication time-delay would affect the characteristic of system consensus convergence. When the time-delay is less than the maximum allowable time-delay, system can reach consensus convergence, otherwise, the system will not converge.

(2) The time-delay parameter has little impact on the system consensus convergence when the time-delay is relatively small. However, the system consensus convergence speed would change significantly when the time-delay parameter is near the maximum allowable time-delay.

(3) The system maximum allowable time-delay parameter is relevant to the maximum eigenvalue of the network Laplacian matrix, which means that the parameter is also related to the connectivity of the network.

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