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Improved average consensus algorithm based distributed cost optimization for loading shedding of autonomous microgrids

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ABSTRACT

This paper addresses a new distributed cost optimization (DCO) method for load shedding (LS) of an islanded microgrid considering cost. A two-layer improved average consensus algorithm (IACA) of multi-agent system (MAS) is proposed, and the consensus characteristic of which is analyzed in detail. With the global information discovered in the first layer of the IACA, the DCO of LS can be solved by using the synchronization processing of the IACA in the second layer. PSCAD/EMTDC-based simulation models are built to study the value settings of consensus constants and the performances of the proposed DCO method. Simulation results verified the convergence improvement of the IACA and the effectiveness of the proposed DCO.

Introduction

There will be more microgrids in future power systems, including grid-connected microgrids and islanded microgrids [1,2]. An islanded microgrid is more likely to occur a disturbance because of the randomness and uncertainty of renewable distributed generators (DGs) and the low-inertia of the microgrid [3]. Thus a sudden change in generation or load poses a challenge for stabilizing the frequency of an islanded microgrid. Furthermore, a large disturbance could result in a rapid frequency drop or even microgrid blackout [4]. The best way to maintain the stability of the frequency response is to execute a load shedding (LS) scheme [5,6].

Accordingly, many studies focus on adaptive and intelligent LS schemes to avoid the instability caused by shedding an improper amount of load. On one hand, the magnitude of the active power unbalance estimation method based on rate of change of frequency (ROCOF) and system inertia constant was proposed in [7–10], by using the estimated value the amount of load shedding can be determined and an accurate and quick LS can be implemented in a central control manner. On the other hand, a multi-agent system (MAS) based LS is introduced to obtain adaptive LS, the control modes of the MAS-based LS are centralized or distributed with coordination [11,12]. The centralized scheme requires a central controller, which easily suffers from a failure to handle the huge amount of data. Moreover, taking the uncertainty of intermittent renewable energy resources into consideration, a generation fluctuation may result in unintentional structure changes, which will further increase the burden on centralized strategy. Distributed coordination theory is realized based on consensus and cooperation theory in networked MAS, and the average consensus algorithm such as Metropolis method and improved Metropolis method were applied to discover global information, thus a local decision-making can be made considering the global information [13,14]. On this basis, many distributed cooperative schemes are proposed, in [15], the authors proposed a consensus theory based multi-agent coordination scheme for information discovery in microgrids via wireless networks, the Metropolis method and pairwise average was applied accordingly. In [16], the authors proposed a novel model of a distributed demand side management mechanism that allows agents, by adapting the deferment of their loads based on grid prices, to coordinate in a distributed manner. In [17], the authors proposed an improved average-consensus theorem based global information discovery method and a distributed multi-agent-based LS algorithm, which can make efficient LS decision based on discovered global information. However, the distributed scheme with a leader–follower structure, which uses a leader agent to gather information from all of the other local agents

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Nomenclature

LS	load shedding	DER	distributed energy resource
DCO	distributed cost optimization	MT	micro turbine
MAS	multi-agent system	WT	wind turbine
IACA	improved average consensus algorithm	PV	photovoltaic
MC	marginal cost	MH	mini hydro
DG	distributed generator		

and sum it to obtain the global information, raises similar concerns about system performance and reliability when possible malfunctions and attacks occur at the leader agent like central controllers. In [18], the authors proposed a two layer consensus based fully distributed LS scheme without leader agent, advantages of a fully distributed scheme include the ability to survive uncertain disturbances and fully distributed data updating, which leads to efficient information sharing and eventually a faster decision-making process and operation.

Recently, the cost prioritized schemes in generation side for a rural or islanded microgrid attracted special attention, in [19], two cost-prioritized droop schemes for distributed generators (DGs) were proposed; in [20], a distributed subgradient-based coordination of multiple renewable generators considering different generation cost was proposed in a microgrid. With regard to the LS schemes, a cost prioritized based optimal LS in customer side also deserves more attention. Typically, the different important grades (non-vital/semi-vital/vital) [8] and the different stages of load (three stages of load) [10] were taken into accounts during the LS scheme, the cost of LS and the willing of customers to shed load are also needed to be considered during the implementation of the distributed LS [21,22] in customer side. The proposals of this study are inspired from the multi-stage LS scheme [10] and the distributed cooperative algorithm [13,14,17,18], and the main objectives are as follows: (1) to implement a practical LS considering the cost of LS and the customers' willing to shed load; and (2) to implement a fully distributed LS without leader or virtual leader.

This study proposed a two-layer improved average consensus algorithm (IACA) based DCO method for LS of an islanded microgrid to overcome the mentioned shortcomings caused by leader agents. It can implement an adaptive LS considering the cost and marginal cost of LS and the willing of customers to LS in customer side. Several related problems have been addressed in this study, including the convergence improvement of consensus method, the DCO for LS considering cost and marginal cost, and the adaptation of DCO during plug-and-play operations. Representative cases are evaluated to testify the improvement of IACA and the effectiveness of the proposed DCO method.

The rest of the paper is organized as follows: Section 'Two-layer IACA based DCO for LS' introduces on the proposed two-layered IACA based DCO of LS; Section 'Case studies' illustrates and simulates the proposed DCO in different cases; the conclusions are duly drawn in Section 'Conclusion'.

Two-layer IACA based DCO for LS

In this study, the two-layer IACA of MAS is proposed to implement the distributed LS of an islanded microgrid. Compared with a centralized scheme which coordinates its local agents by central control agent, the proposed distributed scheme coordinates its distributed agents based on IACA based global information sharing and the synchronization processing of IACA. For the MAS in this study, every agent knows its corresponding power outputs and load conditions, but does not have direct access to the global information since it can only communicate with its immediate neighboring agents. Thus, the main challenge with the design of DCO and distributed LS is to discover the global information and realize optimization through information exchange between distributed agents. According to the two-layer IACA strategy, in the first layer, the local agents monitor the power disturbances throughout the microgrid and share the global information to each agent. While in the second layer, the amount of load to be shed is optimized in a distributed manner based on the IACA, considering the cost of each load. Through the global information shared in the first layer, every agent in the second layer can make decision locally according to the global information without the coordination of a leader. Meanwhile the DCO can be implemented by using the synchronization processing of IACA in a fully distributed manner in the second layer.

Fig. 1 illustrates the flowchart of the two-layer IACA based DCO for LS of an islanded microgrid. The corresponding steps of the proposed DCO are described as follows:

Step 1: Firstly global information (the total active power deficiency P_{DEF}) is monitored by the corresponding faulty agent when an active power deficiency or shortage occurs in an islanded microgrid.
Step 2: In this step, through the IACA based distributed global information sharing, the total active power deficiency P_{DEF} of the islanded microgrid is shared among MAS when the average consensus is reached in the first layer IACA.
Step 3: Ranked in the second layer of IACA, each agent evaluates its corresponding cost and marginal cost of load shedding locally according to the cost and marginal cost functions.
Step 4: The DCO of LS is solved by using the synchronization processing of the IACA, and the optimal results will be reached when the marginal cost of each load agent converges to a common value asymptotically.
Step 5: Lastly based on the results calculated by DCO in Step 4, the distributed optimal LS can be implemented for the islanded microgrid.

The first layer: IACA based global information sharing

The average consensus algorithm which relies on local information of agents are used to guarantee the global information be shared in a distributed way. To adapt for the changes of the communication topologies, we have studied ACA method [14] and NNCA method in [18] respectively. In this study an IACA is chosen to achieve the global information in MAS with communication constraints and improve the convergence rate. The IACA based global information sharing and the corresponding *Lyapunov* stability proof is described in Fig. 2.

In Fig. 2, $p_i \in R$ denotes the state variable of agent i; $i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, n$; k is the discrete-time index; $p_i^{[k]}$ and $p_i^{[k+1]}$ are the information shared by agent i at iteration k and $k+1$ respectively, $p_i^{[k]}$ is the information of agent j; $P^{[k]}$ is information sharing matrix; w_{ij} is the coefficient for information exchanged between