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Article

Multiagent-Based Distributed Load Shedding for Islanded Microgrids

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Abstract: This paper addresses a multiagent-based distributed load shedding scheme to restore frequency for the microgrids during islanded operation. The objective of the proposed scheme is to realize a distributed load shedding considering its associated cost and the capacity of the flexible loads. There are two advantages of the proposed scheme: (1) it is a distributed scheme using average-consensus theorem, which can discover the global information when only communications between immediate neighboring agents are used, moreover it can meet the requirements of plug-and-play operations more easily than a centralized scheme; (2) it is a new adaptive load shedding through the comprehensive weights which take into accounts the cost of load shedding and the capacity of flexible loads, these comprehensive weights are evaluated locally by making use of the adaptability and intelligence characteristics of agents. Simulation results in power systems computer aided design (PSCAD) illustrate the validity and adaptability of the proposed load shedding scheme.

Keywords: average-consensus theorem; distributed load shedding; islanded microgrids; multiagent

1. Introduction

The active power imbalance between generation and loads caused by insufficient generation, sudden load change and faults easily occur in islanded microgrids, and it may lead to islanded microgrid collapse [1–4]. A load shedding scheme is globally accepted as one of the effective emergency control schemes to handle this situation [5]. Various kinds of load shedding schemes have been proposed during the past years, which can be classified into two types, namely centralized load shedding scheme and distributed load shedding scheme, respectively [6]. In [7–9], a centralized method was proposed to determine the most appropriate loads to be shed during under-frequency and under-voltage conditions. Although the centralized control scheme may seem like an appropriate solution in coordinating generators and loads, however, it is costly and suffers from failures due to requiring a central controller. Moreover, the centralized scheme cannot easily handle structural changes of microgrids. Due to the plug-and-play operations and the uncertainty of distributed energy resources (DERs), the uncertain changes of microgrid topology may further increase the burden of centralized scheme. Thus, the distributed scheme seems like a better solution for the islanded microgrids [10]. Multiagent system is one of the most popular solutions for distributed load shedding [11–13]. The multiagent-based distributed load shedding schemes have been studied to maintain the supply-demand balance of an islanded microgrid [14–16]. However, the cost of load shedding [17,18] and the capacity of the flexible loads are needed to be considered during the implementation of the distributed load shedding.

This paper proposes a new multiagent-based distributed load shedding scheme for islanded microgrids. First, by using the average-consensus theorem based distributed information processing method, the global information can be discovered with only neighboring agents communications. Secondly, the comprehensive weights of load shedding are determined locally based on the cost of load shedding and the capacity of flexible loads. Lastly, the proposed distributed load shedding strategy is implemented in a distributed manner according to the global information and the comprehensive weights. Simulation results in power systems computer aided design/electromagnetic transients including direct current (PSCAD/EMTDC) are built to illustrate the validity of the proposed method.

The rest of the paper is organized as follows. Section 2 presents the multiagent-based distributed load shedding method, two related problems including the distributed information processing method and the local evaluation of the comprehensive weights are studied in this section. Section 3 provides the simulation results. The conclusions are provided in the last section.

2. Multiagent-Based Distributed Load Shedding

2.1. Distributed Information Processing Method

In this study, the main challenge with the design of distributed load shedding scheme is to discover global information for a multiagent-based microgrid with only neighboring communications. Thus, a new distributed information processing method for multi-agent system is proposed to meet this challenge, and the stability of the proposed method is proved. The proposed method not only can obtain stable distributed information processing, but also can adapt to changes of communication topologies.

The average-consensus theorem which relies on local information of agents are used to guarantee the global information be discovered in a distributed setting [15]. Assuming that $x_i \in R$ denotes the state variable of agent *i*, the distributed information processing of agent *i* can be represented as Equation (1):

$$x_i^{k+1}(t) = x_i^k(t) + \sum_{j \in N_i} \alpha_{ij} \left[x_i^k(t) - x_j^k(t) \right] \tag{1}$$

where $i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, n$; n is the total number of agents; k is the discrete-time index; x_i^k and x_i^{k+1} are the information shared by agent i at iteration k and k+1 respectively; x_j^k is the information sharing of agent j; α_{ij} is the coefficient for information exchange between neighboring agents i and j, if agents i and j are connected through a communication line, otherwise $\alpha_{ij} = 0$, and N_i are the indexes of agents that are connected to agent i.

Accordingly, the distributed information processing of the multiagent-based microgrid can be expressed as Equation (2):

$$\begin{aligned} X^{k+1}(t) &= X^k(t) + A \times X^k(t) = (I + A)X^k(t) \\ &= A^* \times X^k(t) \end{aligned} \tag{2}$$

where X^k is the information matrix; I is the identity matrix; A^* is the updating matrix, that satisfies the constraints, $\Sigma_i \alpha_{ij} = 1$ and $\Sigma_j \alpha_{ij} = 1$, and the coefficients are defined according to the communication topologies. Therefore, this updating matrix is needed to be properly designed to obtain a stable information processing and adapt to changes of communication topologies.

For stability analysis, a positive definite Lyapunov function is defined as in Equation (3):

$$\begin{aligned} L^k &= (X^k)^T X^k \\ \Delta L^k &= \left[\left(X^k\right)^T \left(A^T A - I\right) X^k \right] \le 0 \end{aligned} \tag{3}$$

A new adaptive updating method is proposed in this study to adapt to changes of communication topologies; the corresponding adaptive updating method is represented in Equation (4):

$$\alpha_{ij} = \begin{cases} \dfrac{2-\beta}{n_i + n_j} & j \in N_i \\ 1 - \displaystyle\sum_{j \in N_i} \dfrac{2-\beta}{n_i + n_j} & j = i \\ 0 & j \notin N_i, j \ne i \end{cases} \tag{4}$$

where n_i and n_j are respectively the numbers of agents in the neighborhood of agents i and j, which are the information of agent i and its neighbors; β is the convergence constant, which bounds between zero and two. Therefore each agent can update its corresponding weight locally when its neighborhood is changed. The Lyapunov function in Equation (3) can be derived as follows:

$$\begin{aligned} &\text{If} \quad \alpha_{ij} = \frac{2-\beta}{n_i + n_j}, i \ne j \quad \textit{and} \quad 0 < \beta < 2 \\ &\text{Then} \quad \Delta L^k = \left[\left(X^k\right)^T \left(A^T A - I\right) X^k \right] \\ &\le -\sum_{i=1}^{n} \sum_{j=1}^{n} \left[\left(\alpha_{ij} + \alpha_{ij}^2\right) \left(x_j^k - x_i^k\right)^2 \right] + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\left(n_i + n_j - 2\right) \alpha_{ij}^2 \left(x_j^k - x_i^k\right)^2 \right] \\ &\le -\sum_{i=1}^{n} \sum_{j=1}^{n} \left[\left(\frac{2 - \left(n_i + n_j\right) \alpha_{ij}}{2} \right) \alpha_{ij} \left(x_j^k - x_i^k\right)^2 \right] \\ &\le -\sum_{i=1}^{n} \sum_{j=1}^{n} \left[\frac{\beta(2-\beta)}{2(n_i + n_j)} \left(x_j^k - x_i^k\right)^2 \right] \\ &\le 0 \end{aligned} \tag{5}$$

The Lyapunov verification in Equation (5) shows that the proposed updating method satisfies the condition represented in Equation (3), which means the designed updating method for average consensus algorithm is stable. Thus the proposed distributed information processing method can guarantee stable information exchange, and the value x_i will converge to the same average value when convergence is reached, as shown in Equation (6):

$$X_A = \frac{1}{n}\sum\nolimits_i x_i^0 (1, \cdots 1, \cdots 1)^T \tag{6}$$

where X_A is the final average values achieved by the average-consensus theorem based information processing; x_i^0 is the initial value of the ith load.

Note that agent keeps updating its information processing until $(x_i^k - x_j^k)$ becomes zero according to Equation (2), which may take a long time before the exact equilibrium is reached. Thus, for distributed information processing in this study, the information processing terminates once $(x_i^k - x_j^k)$ is close to 0, accordingly, a terminating criterion is defined as in Equation (7):

$$\sum_{l=k-r}^{k} \left| x_i^l - x_i^{l-1} \right| \leq \sigma \tag{7}$$

where k is a integer that specifies the number of iterations and σ is a small real number next to zero, increasing the value of σ may improve the convergence speed but reduce convergence accuracy, thus, the value setting of σ needs to be determined giving consideration to both the convergence speed and accuracy. Generally, the value of σ is set bounding between 10^{-3} and 10^{-6}. When Equation (7) is satisfied, each agent terminates its information processing and an average consensus is reached.

Note that the information discovered by the distributed information processing is the average value of the global information. Thus each agent needs to multiply the total number of agents that participate in global information processing n to get the global information. Assuming that the number i is the unique index for each agent, thus, each agent can achieve the total number n by the distributed information processing as follows:

$$N_{Ai} = \frac{i}{n} \Rightarrow n = {}^{i}\!/\!_{N_{Ai}} = {}^{i}\!\Big/\!_{\frac{i}{n}} \tag{8}$$

where N_A is average value of the index i discovered by the ith agent.

It is noteworthy that the number n is global information, which reflects the number of agents that participate in the information processing, which is the key factor to meet the requirements of plug-and-play operations. Through the adaptive updating of n, the proposed method can work properly when the communication structure of microgrid changes during the global information discovery process. More specifically, when a new agent is added and marked as $(n + 1)$, the number n changes to $(n + 1)$, thus the N_{Ai} discovered by the ith agent changes to $[i/(n + 1)]$ accordingly. Meanwhile, only the $(n + 1)$th agent and its neighbors need to update the corresponding information during the global information processing. If a plug out operation happens, the N_{Ai} discovered by the ith agent changes to $[i/(n - 1)]$ for n changes to $(n - 1)$. The unique indices of the existing agents do not need to change during the information discovery, only the neighbors of the plug out agent need to update the local information. In this way, each agent can know the number n and adapt for the communication topology changes locally.

2.2. Local Evaluation of the Comprehensive Weight

In order to get an adaptive distributed load shedding, each agent should make decisions according to the discovered global information and its local operation information. Therefore, a comprehensive weight is proposed to take the local information into considerations. In this paper, local information including the cost of load shedding and the capacity of flexible load are considered, and the cost index and the capacity index are evaluated accordingly. The proposed comprehensive weight is evaluated by taking into accounts both the cost index and capacity index, the local evaluation of the comprehensive weight is described as follows:

First, assuming that the cost of load shedding can be described as follows [17,18]:

$$F_i\left(L_{Ci},\chi_i\right)=\tau_1 {L_{Ci}}^2+\tau_2(L_{Ci}-L_{Ci}\chi_i) \qquad i=1,2,\cdots,n \tag{9}$$

where i = 1,2, …,n; n is the total number of flexible loads; L_{Ci} is amount of load shedding of the ith load; F_i is the cost function of the ith flexible load when L_{Ci} is shed; τ_1 and τ_2 are the constants; χ_i is the willing coefficient for load shedding of the ith flexible load, which expresses willing to shed load.

Thus, the cost index of the ith load can be determined by the cost functions as in Equation (10):

$$\eta_i=\frac{K_{F_i}}{K_F^T}=\frac{\dfrac{1}{F_i^*}}{\sum_i\dfrac{1}{F_i^*}}=\frac{\dfrac{1}{\tau_1(L_{Ci}^*)^2+\tau_2(L_{Ci}^*-L_{Ci}^*\chi_i)}}{\sum_i\dfrac{1}{\tau_1(L_{Ci}^*)^2+\tau_2(L_{Ci}^*-L_{Ci}^*\chi_i)}} \qquad i=1,2,\cdots,n \tag{10}$$

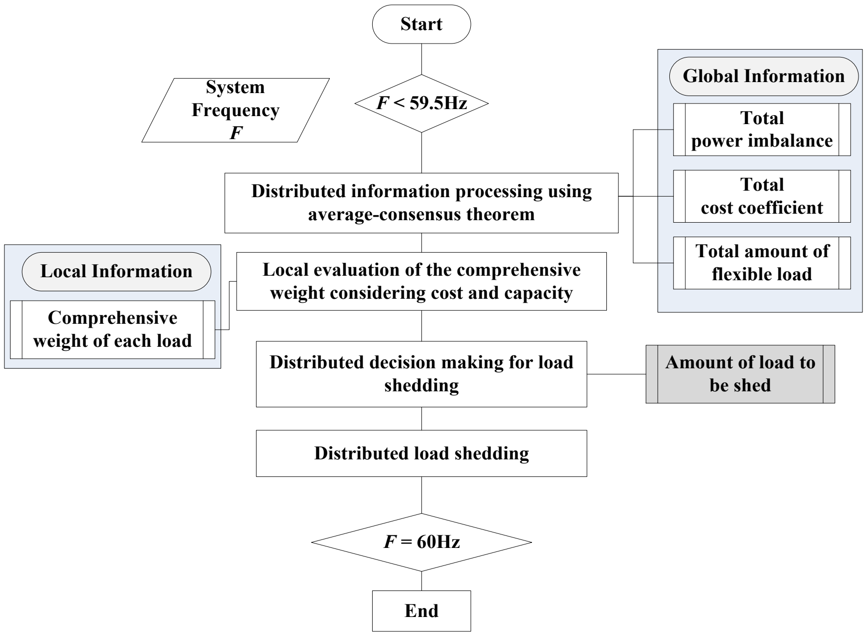
where η_i is the cost index of the ith load; K_{Fi} is the cost coefficient of the ith load; K_F^T is the total value of the cost coefficients of all loads. Note that K_{Fi} is the local information of the ith load, which is calculated by each agent locally; while K_F^T is a global information which is discovered by the proposed distributed information processing method, as described in Figure 1; L_{Ci}^* is amount of load shedding of the ith load for the calculation of cost coefficient; F_i^* is the cost function of the ith flexible load when L_{Ci}^* is shed, note that the cost coefficient is calculated when each load sheds the same amount of load.

Secondly, the capacity index is calculated according to the amount of flexible loads as in Equation (11):

$$\lambda_i=\frac{C_{FLi}}{C_{FL}^T}=\frac{C_{FLi}}{\sum_i C_{FLi}} \qquad i=1,2,\cdots,n \tag{11}$$

where λ_i is the capacity index of the ith load; C_{FLi} is the amount of flexible load of the ith load; C_{FL}^T is the total amount of flexible load of the whole system. As mentioned in Equation (10), C_{FLi} is also evaluated locally and C_{FL}^T is discovered by the distributed information processing method.

Figure 1. The flowchart of the proposed multiagent-based load shedding.



Lastly, the comprehensive weight of load shedding of the *i*th load can be determined as follows:

$$\phi_i = \varepsilon_{i1}\lambda_i + \varepsilon_{i2}\eta_i \quad i = 1, 2, \cdots, n \tag{12}$$

where Φ_i is the comprehensive weight of load shedding of the *i*th load; ε_{i1} is the cost weight of the *i*th load; ε_{i2} is the capacity weight of the *i*th load, which are determined by each agent locally according to its concerns on cost and capacity.

2.3. Flowchart of the Proposed Multiagent-Based Distributed Load Shedding

Note that the global information processing method and the local evaluation of comprehensive weight are the key factors for the proposed distributed load shedding, because each distributed agent only knows its local information and information of its neighboring agent.

Assume that the agents of the multi-agent system in this study are autonomous and proactive, thus, they not only can make the local evaluation of the local information, but also can discover the global information in a distributed way. The main functions of the agent are described as follows:

- Detect power imbalance and collect operation and control data;
- Exchange data with neighbors for distributed information processing;
- Discover the global information including the active total power imbalance P_{IB} as in Equation (13) the total cost coefficient K_F^T as in Equation (10) and the total amount of flexible loads C_{FL}^T as in Equation (11);
- Make local evaluation of the cost index as in Equation (10), the capacity index as in Equation (11) and comprehensive weight as in Equation (12).

Through the discovered global information and the comprehensive weights, the distributed load shedding can be implemented. The flowchart of the proposed distributed load shedding is described as follows:

Step 1: Through the average-consensus theorem based information processing, the global information including the active total power imbalance P_{IB}, the total cost coefficient K_F^T as in Equation (10) and the total amount of flexible loads C_{FL}^T as in Equation (11) are all discovered in a distributed manner;

The total active power imbalance P_{IB} can be described as Equation (13):

$$P_{IB} = P_{Gen} - P_{Load} \tag{13}$$

where P_{Gen} is the total power generation of all the generators; P_{Load} is the total amount of loads.

Step 2: Each distributed agent evaluates its comprehensive weight Φ_i of load shedding considering its associated cost and the capacity of the flexible loads, in addition its corresponding concerns on cost and capacity;

Step 3: Taking into accounts the comprehensive weight Φ_i in step 2 and P_{IB} discovered in step 1, each agent can make decisions locally to determine the amount of load to be shed. The amount of load to be shed of the *i*th load can be derived as:

$$P_{LSi} = \phi_i P_{IB} \qquad i = 1, 2, \cdots, n \tag{14}$$

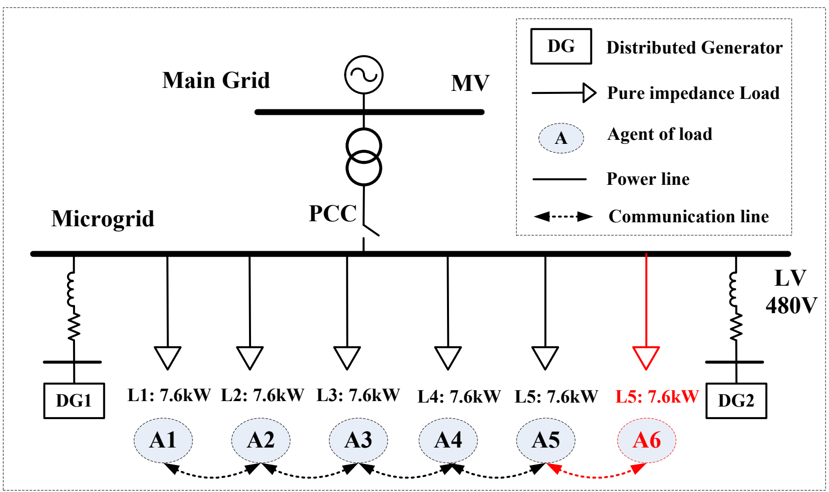
where P_{LSi} is the amount of load to be shed of the *i*th load;

Step 4: The multiagent-based distributed load shedding is implemented based on the decisions made by step 3 to get the frequency restoration after accidents.

3. Case Studies

The simulation models on PSCAD/EMTDC platform are built to verify the validity of the proposed scheme. The configuration of the simulation microgrid is shown in Figure 2, which is built by referring to the structure of the Wisconsin CERTS microgrid [19].

Figure 2. Simulated microgrid.



3.1. Case A: Overload

At first, distributed generators (DG) 1 operates in voltage/frequency (V/F) control mode to maintain the stability of the islanded microgrid, and DG2 works in active power and reactive power (PQ) control mode. When t = 3 s, the islanded microgrid occurs an overload disturbance at load 2, the system frequency still drops down lower than 59.5 Hz even with the V/F control of DG1, thus the load shedding needs to be implemented to restore the frequency of the autonomous microgrid.

The parameters of simulation case A and case B are presented in Tables 1 and 2 as follows:

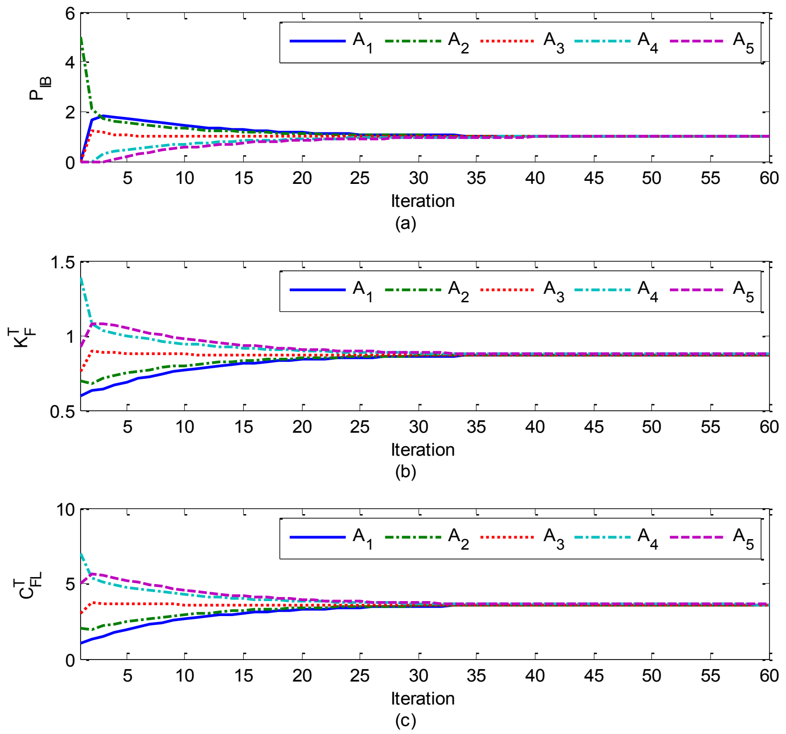
Table 1. Parameters of loads in Case A.

Load Number	**Case A**			
	χ_i	C_{FLi}/kW	ε_{i1}	ε_{i2}
1	0.1	1	0.3	0.7
2	0.3	2	0.3	0.7
3	0.4	3	0.3	0.7
4	0.9	7	0.3	0.7
5	0.6	5	0.3	0.7

Table 2. Parameters of loads in Case B.

Load Number	**Parameters of loads in Case B**			
	χ_i	C_{FLi}/kW	ε_{i1}	ε_{i2}
1	0.1	1	0.6	0.4
2	0.3	2	0.6	0.4
3	0.4	3	0.6	0.4
4	0.9	7	0.6	0.4
5	0.6	5	0.6	0.4
6	0.5	4	0.6	0.4

Figure 3. The distributed global information processing of Case A. (**a**) The information processing of the active total power imbalance P_{IB}; (**b**) the information processing of the total cost coefficient K_F^T; (**c**) the information processing of the total amount of flexible loads C_{FL}^T.



First, the global information including the active total power imbalance P_{IB}, the total cost coefficient K_F^T and the total amount of flexible loads C_{FL}^T are all discovered by the proposed distributed information processing method. In this case, assuming that $\tau_1 = 0.6$, $\tau_2 = 1.2$, $\beta = 0.01$, the iterations of the global information processing are shown in Figure 3:

It can be seen from Figure 3a–c that, through the global information processing method expressed in Subsection 2.1, the average values of the global information including P_{IB}, K_F^T and C_{FL}^T are all discovered when the average consensus is reached. In this case, the number n is discovered according to Equation (8) by each agent as $n = 5$, so the global information can be achieved by multiply 5 and the discovered average values.

Second, with the discovered K_F^T, C_{FL}^T and the local information calculated by each agent, the cost index and the capacity index can be evaluated by Equations (10) and (11), respectively. Therefore, the comprehensive weight Φ_i can be evaluated locally by the method described in Equation (12) as follows:

$$\begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 & 0 & 0 \\ 0 & \varepsilon_{21} & 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{31} & 0 & 0 \\ 0 & 0 & 0 & \varepsilon_{41} & 0 \\ 0 & 0 & 0 & 0 & \varepsilon_{51} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \end{bmatrix} + \begin{bmatrix} \varepsilon_{12} & 0 & 0 & 0 & 0 \\ 0 & \varepsilon_{22} & 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{32} & 0 & 0 \\ 0 & 0 & 0 & \varepsilon_{42} & 0 \\ 0 & 0 & 0 & 0 & \varepsilon_{52} \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix} = \begin{bmatrix} 0.0798 \\ 0.1255 \\ 0.1688 \\ 0.3677 \\ 0.2581 \end{bmatrix} \quad (15)$$

The local evaluation of the comprehensive weight takes into accounts the cost of load shedding and the capacity of flexible load, it also reflects the concerns of cost and capacity.

Figure 4. The performances of the proposed distributed load shedding of Case A. (**a**) The power outputs of DGs; (**b**) the frequency response of the islanded microgrid; (**c**) the voltage responses of DGs; (**d**) the capacity of the flexible loads and the amounts of loads to be shed.

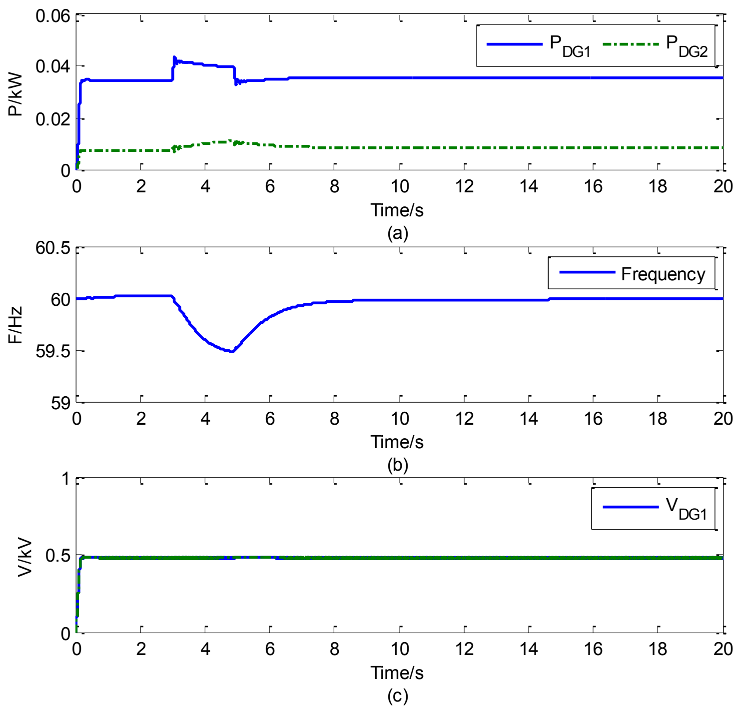
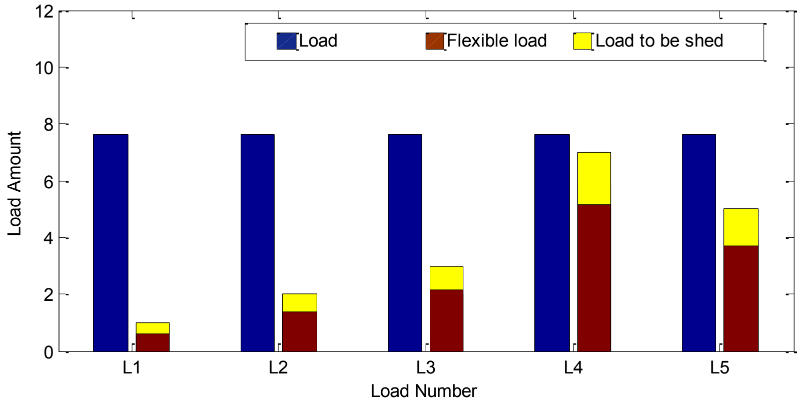


Figure 4. *Cont.*



(d)

Last, the distributed load shedding can be implemented in a distributed manner based on P_{IB} and Φ_i according to Equation (14). Based on the PSCAD-based real-time simulation model of Case A, the performances of the proposed distributed load shedding, including the power outputs and voltage responses of DG1 and DG2 and the frequency response of the islanded microgrid are all shown in Figure 4 as follows:

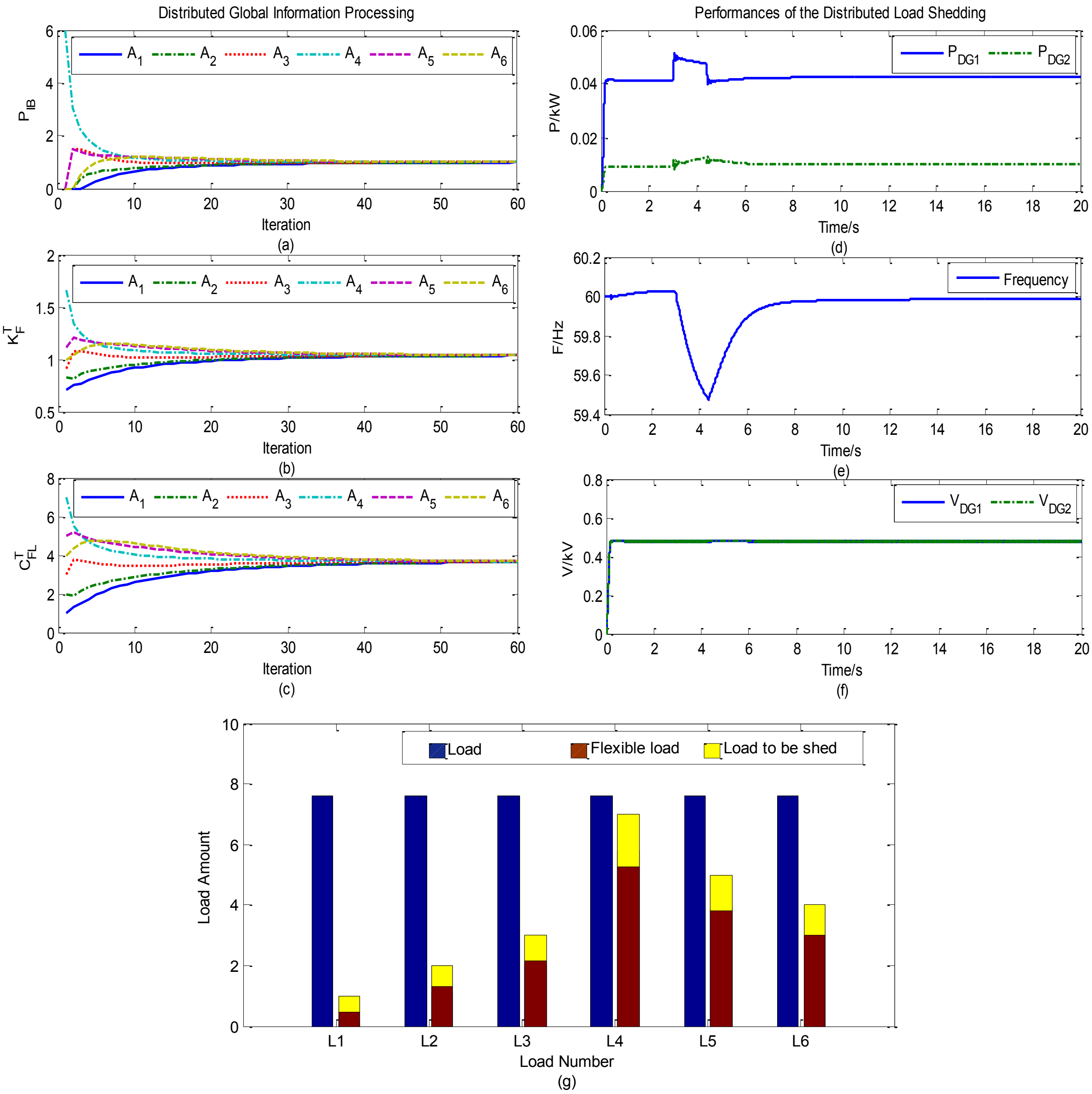
It can be seen from Figure 4a–c that, through the proposed distributed load shedding and the power control of DGs, the frequency and voltage can quickly recover to the rated values after the overload accident. Figure 4d shows the amounts of the flexible load and the amounts of loads to be shed in details. By using the proposed comprehensive weight, the amounts of load to be shed are determined considering both cost and capacity. The amount of load to be shed of Load 1 which has the lowest willing to shed load $\chi_1 = 0.1$ and the minimum flexible capacity $C_{FL1} = 1$ kW is the smallest, while the amount of load to be shed of Load 4 which has the highest willing $\chi_4 = 0.9$ and the maximum flexible capacity $C_{FL4} = 7$ kW is the biggest, as can be observed from Figure 4d. The results in Case A demonstrate that the proposed method can implement a distributed load shedding considering its associated cost and the capacity of the flexible loads.

3.2. Case B: New Load Plugs in Operation

In this case, a new load 6 connects into the islanded microgrid, as a result a new agent added and the communication topology changes accordingly. When $t = 3$ s, the islanded microgrid occurs an overload disturbance at load 4, the load shedding needs to be implemented when frequency drops down lower than 59.5 Hz.

This case focuses on demonstrating the adaptation of the proposed method to meet the requirements for plug-and-play operations in communication topology. The simulation results are all shown in Figure 5:

Figure 5. The distributed global information processing and the performance of the distributed load shedding of Case B. (**a**) The information processing of the active total power imbalance P_{IB}; (**b**) the information processing of the total cost coefficient K_F^T; (**c**) the information processing of the total amount of flexible loads C_{FL}^T; (**d**) the power outputs of DGs; (**e**) The frequency response of the islanded microgrid; (**f**) the voltage responses of DGs; (**g**) the amounts of the flexible loads and the amounts of loads to be shed.



First, to meet the requirement for plug in operation, the proposed information processing method updates its corresponding updating matrix to adapt the plug in operation according to Equation (4), only the new agent 6 and its neighboring agent 5 need to update during the plug in operation. Meanwhile, the number n changes to $(n + 1)$ accordingly and is discovered by each agent based on Equation (8). In this case, assuming that $\tau_1 = 0.5$, $\tau_2 = 1.0$, $\beta = 0.01$. It is observed from Figure 5a–c that, the global information processing method can also discover the global information as Case A even during the plug in operation. Secondly, based on the evaluation method described in

Equations (9)–(12), the comprehensive weights Φ_i are determined by each load locally. Lastly, the amounts of load to be shed are determined in a distributed way by Equation (14), as can be seen from Figure 5g. It is also observed from the Figure 5d–f that, the frequency and voltage can quickly restore to the rated values after the overload accident through the proposed distributed load shedding scheme.

4. Conclusions

A multiagent-based distributed load shedding method is proposed in this study. The implementation of the proposed method is completed based on the global information processing method using the average-consensus theorem and the local evaluation of the comprehensive weight considering cost and capacity. The simulation results demonstrated the advantages of the proposed scheme. First, the global information processing method can discover global information when only communications between immediate neighboring agents are used. Secondly, the distributed scheme can meet the requirements of plug-and-play operations. Thirdly, the distributed load shedding scheme can adapt the local information through the comprehensive weight considering its associated cost and the capacity of the flexible loads.

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Author Contributions

All authors contributed to the work in this manuscript. Xi Wu was the principal investigator; he contributed to the analysis, writing and editing including the overall idea of the manuscript. Ping Jiang provided precious advice on the simulation and thoroughly reviewed the manuscript. Jing Lu accomplished the simulation work.

Conflicts of Interest

The authors declare no conflict of interest.

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