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Article

A Multiagent System for Autonomous Operation of Islanded Microgrids Based on a Power Market Environment

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Abstract: One of the most important requirements of microgrid operation is to maintain a constant frequency such as 50 Hz or 60 Hz, which is closely related to a power balance between supply and demand. In general, microgrids are connected to power grids and surplus/shortage power of microgrids is traded with power grids. Since islanded microgrids are isolated from any power grids, the decrease in generation or load-shedding can be used to maintain the frequency when a power imbalance between supply and demand occurs. The power imbalance restricts the electricity use of consumers in the case of supply shortage and the power supply of suppliers in the case of supply surplus. Therefore, the islanded microgrid should be operated to reduce power imbalance conditions. Meanwhile, the microgrid is a small-scale power system and the employment of skillful operators for effective operation of its components requires high costs. Therefore, automatic operation of the components is effective realistically. In addition, the components are distributed in the microgrid and their operation should consider their owners' profits. For these reasons, a multiagent system application can be a good alternative for microgrid operation. In this paper, we present a multiagent system for autonomous operation of the islanded microgrid on a power market environment. The proposed multiagent system is designed based on a

cooperative operation scheme. We show the functionality and the feasibility of the proposed multiagent system through several tests.

Keywords: microgrid; islanded microgrid; islanded microgrid operation; autonomous operation; multiagent system

1. Introduction

Recently, interest in microgrids with clean power sources such as wind power and solar power has been growing as a new eco-friendly energy system and the microgrid technology has been studied in many countries [1,2].

Electrical and thermal energies are produced in the microgrid but in this paper we focus on power. A microgrid can be operated in a grid-connected mode and an islanded mode. An islanded microgrid means a microgrid disconnected from any power grids by the occurrence of a fault in the interconnected power grid or by geographical isolation, such as on an island. One of the most important requirements of microgrid operation is to maintain a constant frequency such as 50 Hz or 60 Hz, which is closely related to a balance between power supply and power demand. Whenever a power imbalance in the islanded mode occurs, it should be solved by a decrease in generation in the case of supply surplus and load-shedding, which is an intentional reduction of load amounts, in the case of supply shortage. The power imbalance restricts the electricity use of consumers in the case of supply shortage and the power supply of suppliers in the case of supply surplus. Therefore, the islanded microgrid should be operated to reduce the power imbalance.

Attention on autonomous power grids has been growing in power engineering circles in recent years. To implement autonomous systems, multiagent system technology has been studied as a candidate technology in various areas [3–10]. Against this backdrop, multiagent systems for control and operation of the microgrid have been studied [11–18]. Automatic and autonomous operation and control of microgrids based on multiagent systems instead of human operators have some merits for efficient management because microgrids are small-scale power systems and the employment of skillful operators for their components is costly considering the size of the components. Recently, a multiagent system has been developed for the pilot microgrid of Kythnos Island (Greece) [12]. The multiagent system dealt with the intelligent control of the pilot microgrid and showed the feasibility of the application of a multiagent system in a real microgrid.

In this paper, we propose a multiagent system for autonomous operation for an islanded microgrid in a power market environment. In general power systems, operation is planned in the previous interval and the established plan is implemented in the next interval. Components of the power system are controlled according to the established plan. Therefore, operation deals with a longer period than control. Islanded microgrid operation is a special challenge because of some uncertain factors such as stable output control of solar and wind power systems, accurate load forecasting, and load management according to an established plan. Recently, control and forecasting studies related to the uncertain factors have been studied [12,19,20]. We focus on autonomous operation related to operation planning of an islanded microgrid based on a multiagent system and assume that the uncertain factors

can be solved. In this respect, our paper has a different approach from the multiagent system for the pilot microgrid of Kythnos Island [12]. In addition, we consider a competition environment among power suppliers. We establish a cooperative operation scheme for islanded microgrids on a power market environment to reduce power imbalance conditions as a common goal of all participants of the islanded microgrid. The cooperative operation includes an effective choice of storage devices between charge and discharge by announcing the information of a power balance between generation sources and loads. The merit order algorithm is used to decide final suppliers, which is a simple but practical algorithm selecting suppliers by descending order of their bidding prices [17]. We use the Contract Net Protocol (CNP) [21] for the bidding process of suppliers and an information exchange protocol (IEP) for other process among some agents such storage device agents and load agents. For load-shedding in the case of supply shortage, we apply the constrained equal losses (CEL) rule to load-shedding. The CEL is a well-known rule used in the bankruptcy problem dealing with the division of an insufficient estate among claimants [22]. The proposed multiagent system is built on the ADIPS/DASH framework [23,24], which is a repository-based multiagent framework and tested on several operation conditions to show the feasibility and functionality of the proposed multiagent system. The contributions of this paper can be summarized as follows:

- We consider a competition environment among power suppliers for microgrid operation.
- We establish a cooperative operation scheme for islanded microgrids to reduce power imbalance conditions as a common goal of all participants of the islanded microgrid.
- We use the CNP and design an IEP for interactions among agents for islanded microgrid operation.
- The load-shedding scheme based on the CEL is applied to solve supply shortages of the islanded microgrid.
- The proposed multiagent system is built on the ADIPS/DASH framework supplying various convenient functions for building multiagent systems.
- We verify the feasibility of the proposed multiagent system for autonomous islanded microgrid operation through various condition tests.

In Section 2, backgrounds relating to islanded microgrid operation such as concepts of microgrids and islanded operation. The proposed cooperative scheme and a load-shedding scheme based on the bankruptcy problem are explained in detail in Section 3. In Section 4, a multiagent system for microgrid operation is designed and constructed for tests. Various condition tests are performed to verify the functionality and feasibility of the proposed the multiagent system for islanded microgrid operation in Section 5. In Section 6, we provide our conclusions.

2. Islanded Microgrid Operation

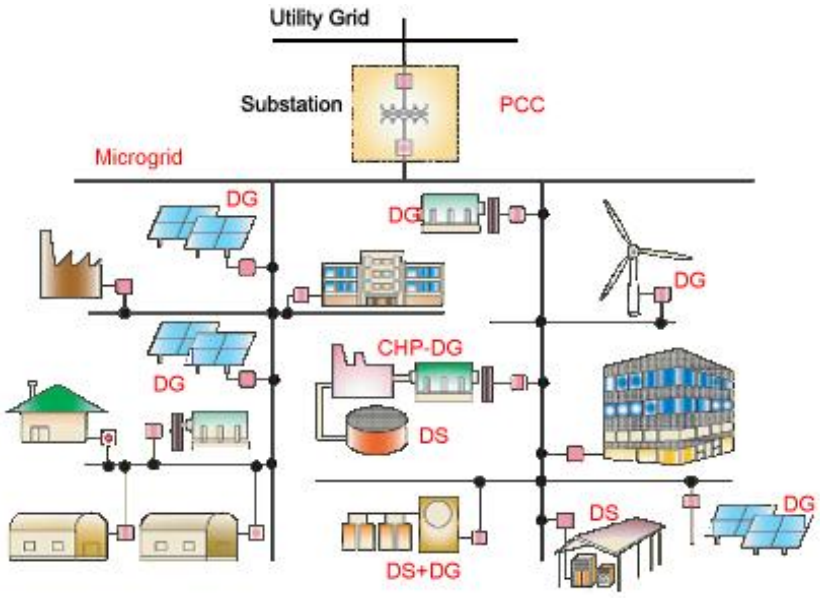
2.1. Microgrid

A microgrid is a small-scale power system composed of distributed generation systems such as solar and wind power, storage devices such as batteries and flywheel energy storage systems, loads such as residential buildings, commercial entities, and industrial compounds, as shown in Figure 1 [25]. DG, DS, and PCC mean a distributed generation system, a distributed storage system, and the point of common coupling in this figure, respectively.

In addition, the Microgrid Operation & Control Center (MGOCC) is considered to manage microgrid operation in this paper [17]. The MGOCC is similar to the Microgrid Control Center (MGCC) described in references [11,12] but its operation functions are more emphasized than in the MGCC. The microgrid has two basic infrastructures: the power line and communication links. The MGOCC and participants exchange information using the communication links.

A microgrid, which is connected to a power grid, is operated in parallel with the power grid in normal conditions. We call this mode the grid-connected mode. The microgrid disconnects the power grid and transfers into the islanded operation mode when a fault occurs in the upstream grid. To meet a power balance between supply and demand is a very important requirement in both operation modes because it is closely related to the system frequency. In general, microgrids should maintain a constant frequency such as 50 Hz or 60 Hz. In this paper, we focus on the islanded mode. Therefore, the utility grid and the PCC of Figure 1 are not considered in this paper.

Figure 1. Microgrid configuration.

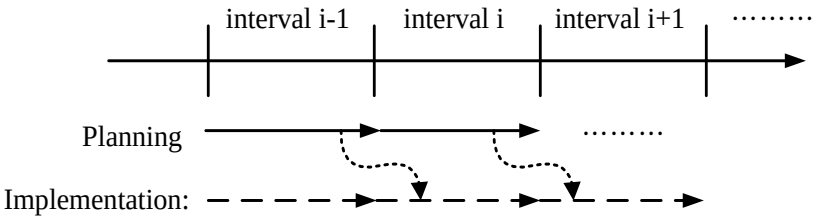


2.2. Islanded Microgrid Operation

We assume an operation procedure for the islanded microgrid as shown in Figure 2 like the operation procedure of power systems [17]. Figure 2 illustrates the operation procedure simply where an operation plan prepared in the previous interval is implemented in the next interval. In Figure 2, the implementation is closely related to control as mentioned in Section 1.

There are three possible operation conditions from the viewpoint of the power balance in the islanded microgrid: equilibrium, supply surplus, and supply shortage. The decrease in generation in the case of supply surplus and load-shedding in the case of supply shortage can be used as available means to meet the power balance. The power imbalance restricts the electricity use of consumers in the case of supply shortage and the power supply of suppliers in the case of supply surplus. In this paper, we consider to reduce the power imbalance conditions as a common goal of all participants of the islanded microgrid.

Figure 2. Operation procedure for islanded microgrid [17].



3. A Cooperative Operation Scheme for Islanded Microgrid

3.1. A Cooperative Operation Scheme

Storage devices have two actions: charge and discharge. In the case of a supply surplus, storage devices can store the electricity by charging to enhance the capacity factor of generation facilities and prepare the supply reserve of the islanded microgrid. On the contrary, they can supply the electricity by discharge in the case of a supply shortage to increase the electricity use of consumers. For this reason, storage devices can play an important role in the islanded microgrid to reduce an imbalance between power supply and power demand. However, it is difficult for storage devices to forecast the power balance and decide their actions to reduce any power imbalance.

One of practical choices is to decide charge or discharge action after checking the power difference between total supply by DGs and total demand by loads. Although the islanded microgrid is operated in a competitive power market environment, the practical choice reduces any power imbalance maximally for the common goal mentioned in Section 2. For this reason, we name the operation scheme based on the idea a cooperative operation scheme.

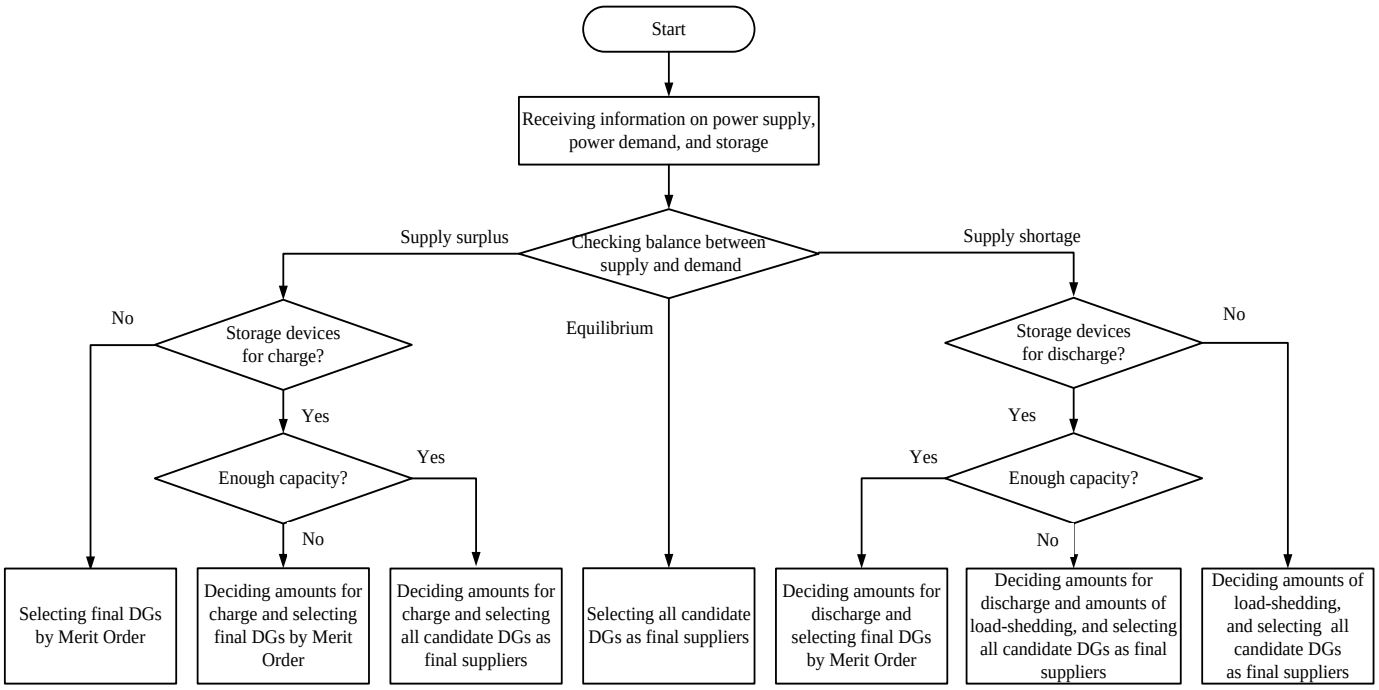
To decide final suppliers in the case of supply surplus on the power market environment, we use the merit order algorithm, which is a widely used dispatching algorithm to select final suppliers by descending order of production costs. We establish steps of a cooperative operation scheme as follows:

- Step 1: Gathering information: The MGOCC receives information on power supply from DGs, power demand from loads, and charged amounts and available amounts for additional charge action from storage devices.
- Step 2: Checking power balance: The MGOCC checks a power balance between supply and demand. If supply is equal to load, all bidding DGs are selected as final suppliers and this dispatch procedure is finished.
- Step 3: Deciding action and amounts of storage devices: The MGOCC decides charge or discharge action of storage devices and their amounts for their action based on the result of checking a power balance and information received from storage devices. If the difference is solved by this decision, all bidding DGs are selected as final suppliers this dispatch procedure is finished.
- Step 4-1: Deciding additional load-shedding: When the supply shortage still remains after Step 3, the MGOCC decides additional load-shedding to solve completely the difference between supply and demand. All bidding DGs are selected as final suppliers and this dispatch procedure is finished.

- Step 4-2: Selecting final suppliers after charge action of storage devices: When the supply surplus still remains after Step 3, the MGOCC selects final DGs as suppliers and their output by the merit order algorithm.

Figure 3 shows the flowchart of the cooperative operation scheme. This operation scheme is used to design a multiagent system for islanded microgrid operation in Section 4.

Figure 3. Cooperative operation scheme.



3.2. Load-Shedding Scheme Based on the Constrained Equal Losses (CEL)

We approach load-shedding in Step 4-1 of the cooperative operation scheme as a bankruptcy problem. The approach was studied in our recent work [26]. In this study, the CEL-based load-shedding algorithm shows a merit of fairness of load-shedding as well as a simple structure. In this paper, we apply the CEL-based load-shedding algorithm.

The bankruptcy problem deals with how to divide short estate to all claimants and it is defined as a pair (c, E), where E is an amount to be divided and $c = (c_1,\cdots,c_N)$ is a set of claims of N agents and is described as:

$$0 \le c_1 \le \cdots \le c_N \text{ and } 0 \le E \le c_1 + \cdots + c_N \tag{1}$$

In order to solve the load-shedding problem, we apply the CEL which is one of rules of the bankruptcy problem. The vector of load division (la^*) for shortage supply power using the CEL rule is defined as:

$$la^* = CEL_i\,(lc, Pa) = \max\{0, lc_i - \lambda\} \tag{2}$$

where Pa is available power and $lc = (lc_1,\cdots,lc_n)$ is the vector of load claims, and λ is chosen so that $\Sigma \max\{0, lc_j - \lambda\} = Pa$.

Finally, the vector of load-shedding of each load (ls^*) is defined as:

$$ls^* = (ls_1^*, \cdots, ls_n^*) = lc - la^* \quad (3)$$

4. Building Multiagent System for Islanded Microgrid Operation

4.1. ADIPS/DASH Framework

An agent is a software (or hardware) entity that is situated in some environment and is able to react autonomously to changes in that environment [27]. A multiagent system is a system composed of two or more agents like a society of agents. Agents communicate with messages using the agent communication language (ACL). In this paper, we use the Agent-based Architecture of Distributed Information Processing Systems (ADIPS)/Distributed Agent System based on Hybrid Architecture (DASH) framework to build a multiagent system for islanded microgrid operation. The followings are main features of the ADIPS/DASH framework [23,24]:

- The ADIPS/DASH is a repository-based multiagent framework for distributed problem solving.
- The repository manages various agents and is responsible to design and realize multiagent systems based on the users' requests.
- An agent is designed and implemented to describe the agent's behavior knowledge for cooperative problem solving together with the agent's meta-knowledge for managing the agent in the repository.
- The ADIPS/DASH framework provides a wrapping mechanism for the agent designers to utilize the external software module such as the Java program as the procedural knowledge of the agent.
- DASH agents can communicate with the different type agents such as FIPA-compliant JADE agents and SAGE agents by using the ACL messages of the DASH agent. The message format of the DASH agent is as follow [28,29]:

  (<performative> :from <agent name> :to <agent name> :content <OAV type data>).

where OAV type data is a set of an object, an attribute of the object, and the value of the attribute.
For effective task management, all agents use a state function (T) as:

$$(s', a) = T(s, e) \quad (4)$$

where s', a, s and e mean the new state, the action, the current state, and the event, respectively [28].

4.2. Design of a Multiagent System

Figure 4 shows a multiagent-based islanded microgrid. To construct a multiagent system, we define an agent set (Ag) as:

$$Ag = \{Ag_{\mathrm{MGOCC}}, AG_{\mathrm{DG}}, AG_{\mathrm{S}}, AG_{\mathrm{L}}\} \quad (5)$$

where Ag_{MGOCC} is the MGOCC agent, AG_{DG} is a set of DG agents (Ag_{DG}), AG_{S} is a set of energy storage device agents (Ag_{S}), and AG_{L} is a set of load agents (Ag_{L}). Ag_{MGOCC} is a manager agent for islanded microgrid operation.

In our work, the CNP is used for interactions between the MGOCC agents and DG agents and an IEP among the MGOCC agent and storage device agents/load agents is used. Table 1 shows two protocols used in the multiagent system. Table 2 shows performatives for a designed IEP (P1) and Table 3 shows performatives for the CNP (P2). To effectively perform interactions, deadlines for tasks are used as shown in Figure 5. Figure 6 shows the message flow among agents based on the P1 and P2.

Figure 4. Multiagent-based islanded microgrid.

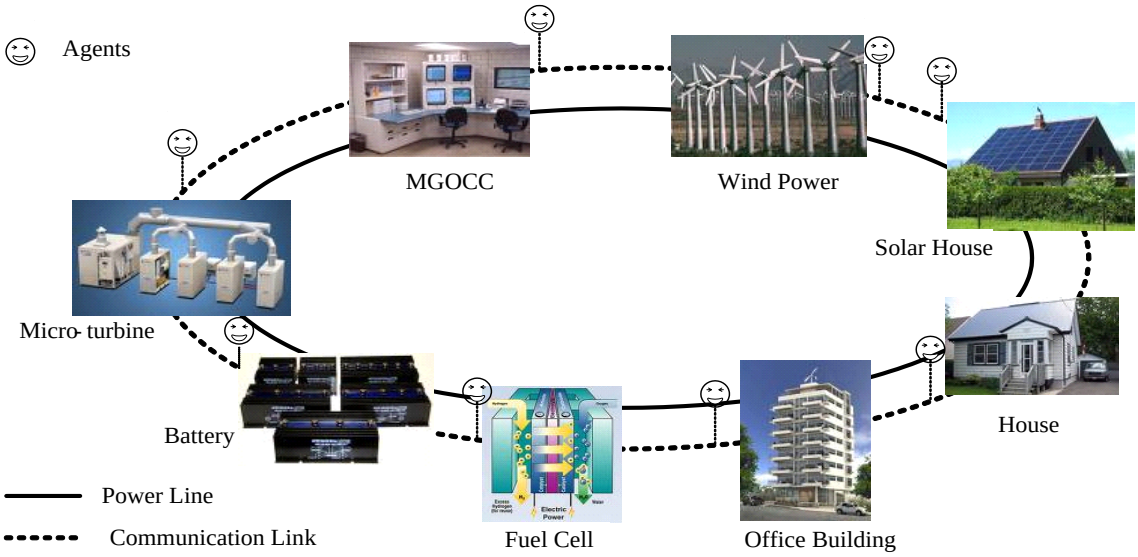


Table 1. Agent communication protocols.

Protocols	Executing Agents	Role of Protocol
P1	Between Ag_{MGOCC} and AG_L, Between Ag_{MGOCC} and AG_S	Used to exchange data, and to distribute control type and its amount between Ag_{MGOCC} and AG_L, AG_S
P2	Between Ag_{MGOCC} and AG_{DG}	Used to select final suppliers among candidate *DG*s

Table 2. Performative for P1.

Performative	Meaning	Remark
RequestInformation	Request for Information about available storage capacity and charged amount	Between Ag_{MGOCC} and AG_L/AG_S
ReceiveInformatoin	Receive information	Between Ag_{MGOCC} and AG_L/AG_S
InformLoad	Inform load amount	Between Ag_{MGOCC} and AG_L
ReceiveLoad	Receive load information	Between Ag_{MGOCC} and AG_L
RequestLoadShedding	Requests for load-shedding	Between Ag_{MGOCC} and AG_L
InformStorage	Inform available capacity and charged amount	Between Ag_{MGOCC} and AG_S
ReceiveStorage	Receive storage information	Between Ag_{MGOCC} and AG_S
RequestCharge	Request for charge	Between Ag_{MGOCC} and AG_S
RequestDischarge	Request for discharge	Between Ag_{MGOCC} and AG_S
ReportLoadShedding	Report load-shedding	Between Ag_{MGOCC} and AG_L
ReportStorageAction	Report action of storage device	Between Ag_{MGOCC} and AG_S

Table 3. Performatives for P2.

Performative	Meaning	Remark
AnnounceTask	Announce to start a new task	
ReceiveTask	Receive a new task	
Bid	Bid for power supply	Bid price and supply amount
ReceiveBid	Receive a bid	
Award	Award contracts	
ReceiveAward	ReceiveAward	
Report	Report the contract	

Figure 5. Deadlines for interactions among agents.

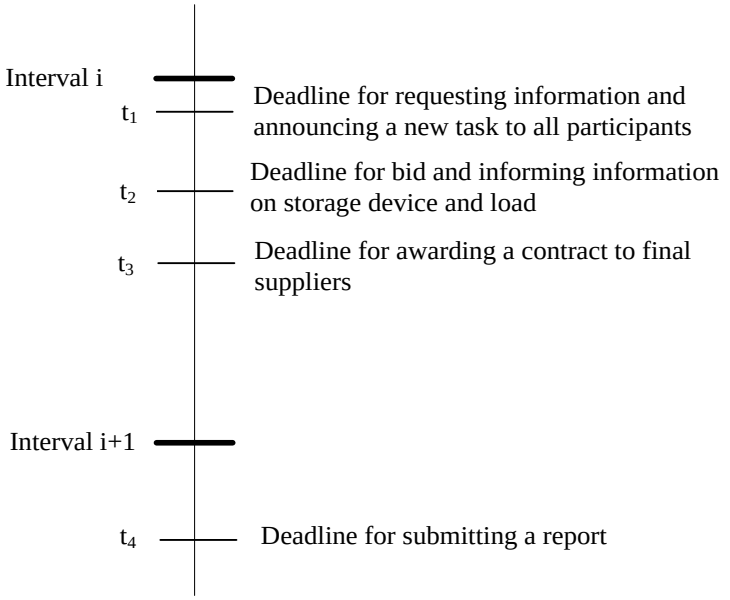
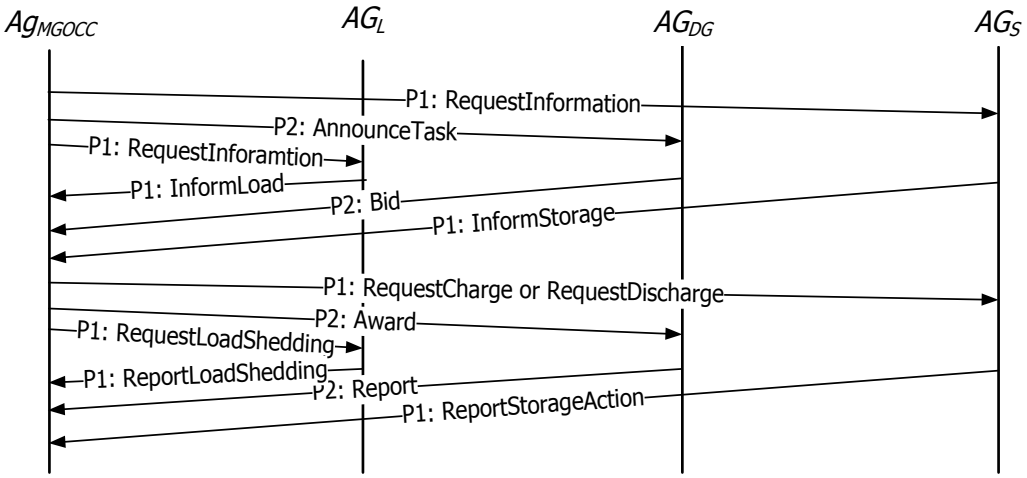


Figure 6. Message flow among agents.

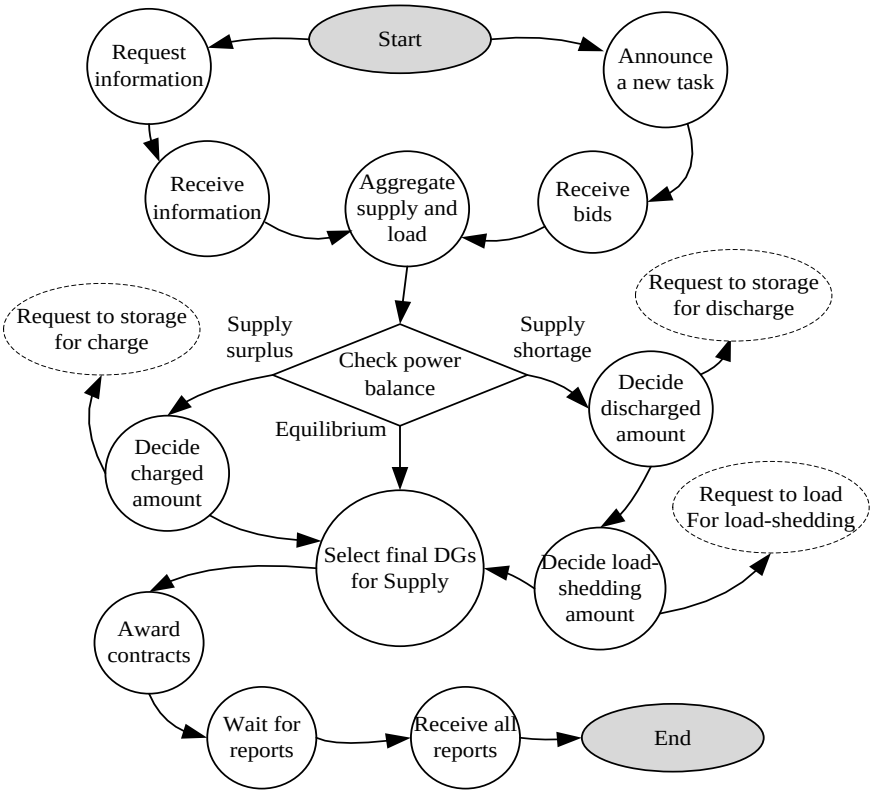


4.3. Design of MGOCC Agent (Ag_{MGOCC}*)*

Ag_{MGOCC} has abilities to manage islanded microgrid operation based on P1 and P2. Detailed his/her tasks are announcing a new task, gathering information, checking a power balance, deciding charge or discharge action of storage devices and their amounts, deciding amounts of load-shedding, selecting final suppliers, distributing operation results, and receiving reports from final suppliers. Figure 7 shows a problem solving flow chart of the MGOCC agent based on the cooperative operation scheme explained in Section 2. The following decision-making functions of Ag_{MGOCC} are designed:

- Checking a power balance;
- Decision of final DG suppliers using the merit order algorism;
- Decision of load-shedding using the CEL.

Figure 7. Message flow among agents.



4.4. Design of DG Agent (Ag_{DG}*)*

Ag_{DG} takes charge of a DG and the following tasks are designed:

- Receiving a new task;
- Bidding a supply amount with a price for the task except out-of-service conditions;
- Receiving a contract from Ag_{MGOCC} when he/she is decided as a final supplier;
- Controlling the generation output (kWh) decided by Ag_{MGOCC} for the next interval;
- Submitting a report after finishing his/her contract.

4.5. Design of Storage Device Agent (Ag_S*)*

Ag_S takes charge of a storage device and the following functions are designed:

- Receiving a request on his/her storage information from Ag_{MGOCC};
- Sending his/her storage information to Ag_{MGOCC};
- Receiving his/her action and amount from Ag_{MGOCC};
- Controlling his/her action (kWh) decided by Ag_{MGOCC} for the next interval;
- Submitting a report after finishing his/her action.

4.6. Design of Load Agent (Ag_L*)*

Ag_L takes charge of a group of consumption devices located in same place. It is assumed that he/she can forecast load during the next interval as mentioned in Section 1. The following functions are designed:

- Receiving a request on his/her load information from Ag_{MGOCC};
- Sending his/her load information to Ag_{MGOCC};
- Receiving his/her final load from Ag_{MGOCC} in the case of supply shortage;
- Managing his/her load (kWh) decided by Ag_{MGOCC} with a ability for management;
- Submitting a report after his/her load-shedding.

4.7. Implementation

Our multiagent system is implemented using the ADIPS/DASH framework as a multiagent platform, the Interactive Design Environment for Agent Designing Framework (IDEA) as a GUI-based interactive environment for the ADIPS/DASH platform, and the Java for user-defined functions [27–29].

5. Experiment

To show the functionality and feasibility of the suggested multiagent system for islanded microgrid operation by the following operation conditions: supply surplus, supply surplus required the decrease in generation, supply shortage, and supply shortage required load-shedding as shown in Cases 1–4.

Figure 8 shows a multiagent-based islanded microgrid for Cases 1–4 and the multiagent system is composed of six agents: an MGOCC agent (Ag_{MGOCC}), two DG agents (Ag_{DG1}, Ag_{DG2}), a DS agent (Ag_{S1}), and two load agents (Ag_{L1}, Ag_{L2}). IMG means the islanded microgrid in Figure 8.

Table 4 shows operation conditions, loads forecasted by load agents and information of a storage device. Here, Char and Aval mean the current charged amount and additionally available charging amount of the storage device, respectively. Table 5 shows production costs and capacities of two DGs. We assume DGs bid their production costs as bid prices for simplicity.

We carry out additional tests with a more complex islanded microgrid shown in Figure 9. The multiagent system is composed of 12 agents: an MGOCC agent (Ag_{MGOCC}), five DG agents (Ag_{DG1}, Ag_{DG2}, Ag_{DG3}, Ag_{DG4}, Ag_{DG5}), two storage device agents (Ag_{S1}, Ag_{S2}), and four load agents (Ag_{L1}, Ag_{L2}, Ag_{L3}, Ag_{L4}).

Figure 8. Configuration of agent-based islanded microgrid for Cases 1–4.

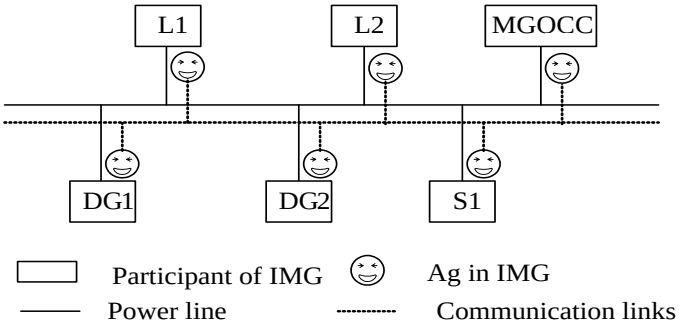


Table 4 Operation condition of Cases 1–4.

Case	Condition	Load (kWh)		Storage (kWh)	
1	Supply surplus	L1: 100	L2: 96	Char: 6	Aval: 4
2	Supply surplus	L1: 96	L2: 96	Char: 6	Aval: 4
3	Supply shortage	L1: 100	L2: 104	Char: 6	Aval: 4
4	Supply shortage	L1: 104	L2: 104	Char:6	Aval: 4

Table 5. DG information of Cases 1–4.

DG	Production Cost (¢/kWh)	Capacity (kWh)
DG1	70	100
DG2	80	100

Figure 9. Configuration of agent-based islanded microgrid for Cases 5–6.

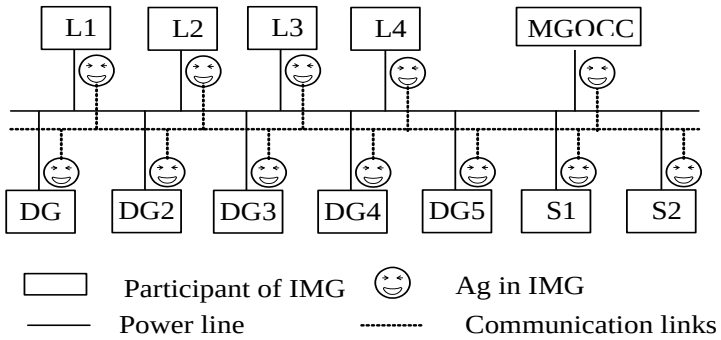


Table 6. Operation condition of Cases 5–6.

Case	Condition	Load (kWh)		Storage (kWh)	
5	Supply surplus	L1: 70 L2: 75	L3: 75 L4: 70	S1: Char: 6	Aval: 4
6	Supply shortage	L1: 100 L2: 110	L3: 105 L4: 102	S2: Char: 3	Aval: 2

In this experiment, we consider two operation conditions: supply surplus requiring a decrease in generation, and supply shortage requiring load-shedding in Cases 5–6. Table 6 shows operation conditions, forecasted loads by load agents and information of storage devices and Table 7 shows production costs and capacities of five DGs, respectively.

Table 7. DG information of Cases 5–6.

DG	Production Cost (¢/kWh)	Capacity (kWh)
DG1	20	50
DG2	50	50
DG3	60	100
DG4	70	120
DG5	80	80

5.1. Case 1—Operation of Supply Surplus

A supply surplus of 4 kW occurs in this case. To meet the power balance for operation of the next interval, the supply surplus should be solved. In this case, we check whether our multiagent system can solve the supply surplus by charge action of a storage device. Figure 10A displayed by MGOCC agent shows the result of Case 1. From the result, we can see that charge of S1 (4 kWh) is decided to solve the supply surplus.

5.2. Case 2—Operation of Supply Surplus Required Additional Decrease of Generation

A supply surplus of 8 kW occurs in this case. To meet the power balance between supply and demand for operation of the next interval, the supply surplus should be solved. We check whether charge of a storage device and the decrease of DGs are reasonably decided to solve the supply surplus.

Figure 10B shows the result of Case 2. From the result, we can see that charge action of S1 (4 kWh) is decided to solve the supply surplus. Also, the decrease of generation of DG2 (4 kWh) is additionally selected by the merit order algorithm.

5.3. Case 3—Operation of Supply Shortage

A supply shortage of 4 kW occurs in this case. To meet the power balance for operation of the next interval, the supply shortage should be solved. In this case, we check whether discharge of a storage device is decided to solve the supply shortage. Figure 10C explains the result of Case 3. This result shows discharge of S1 (6 kWh) and the decrease of generation of DG2 (2 kWh) are decided for this operation condition. This result shows that discharge action of the storage device has a higher priority than the decrease of generation. The priority is decided by problem solving flow of the MGOCC agent shown in Figure 7.

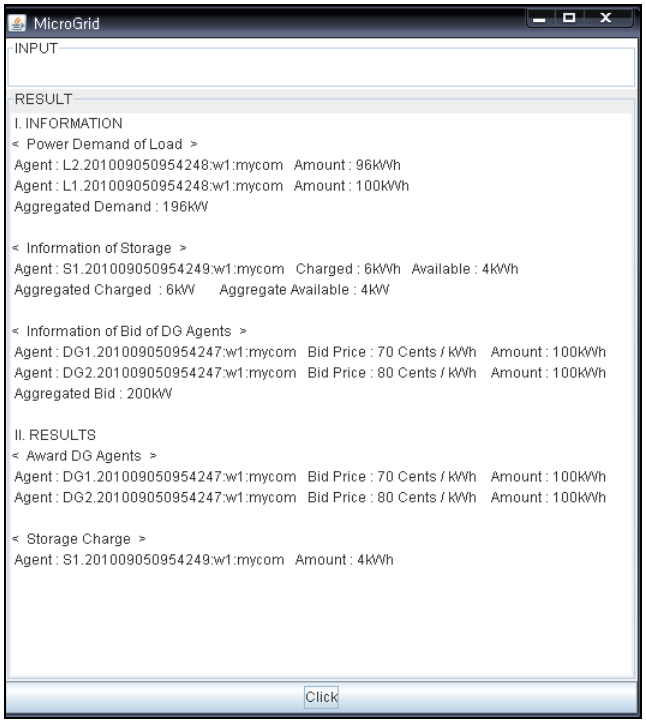
5.4. Case 4—Operation of Supply Shortage Required Load-shedding

A supply shortage of 8 kW occurs in this case. To meet the power balance between supply and demand for operation of the next interval, the supply shortage should be solved. In this case, we check whether discharge of a storage device and additional load-shedding are effectively decided to solve the supply shortage.

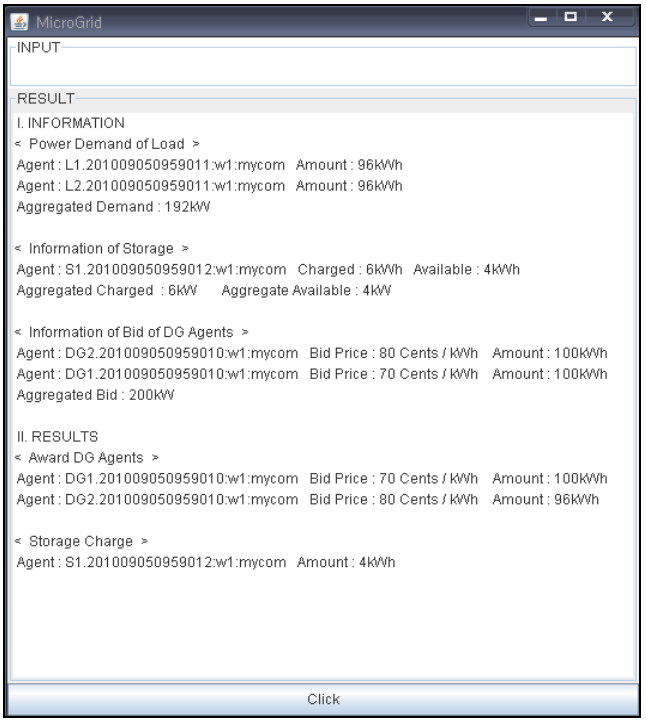
The result of Case 4 as shown in Figure 10D illustrates that discharge of S1 (6 kWh), load-shedding of L1 (1 kWh), and load-shedding of by L2 (1 kWh) are decided to solve the supply shortage as expected.

Figure 10. Result of (**A**) Case 1; (**B**) Case 2; (**C**) Case 3; (**D**) Case 4.

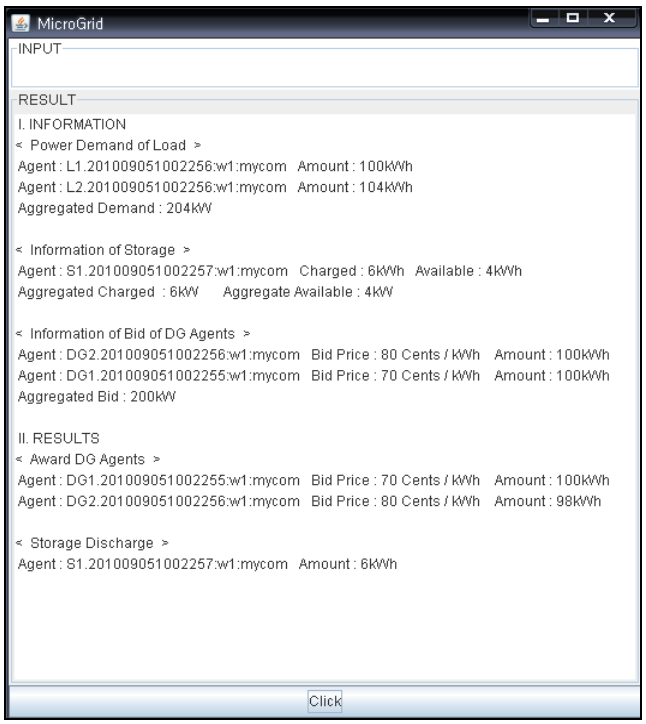
(**A**)



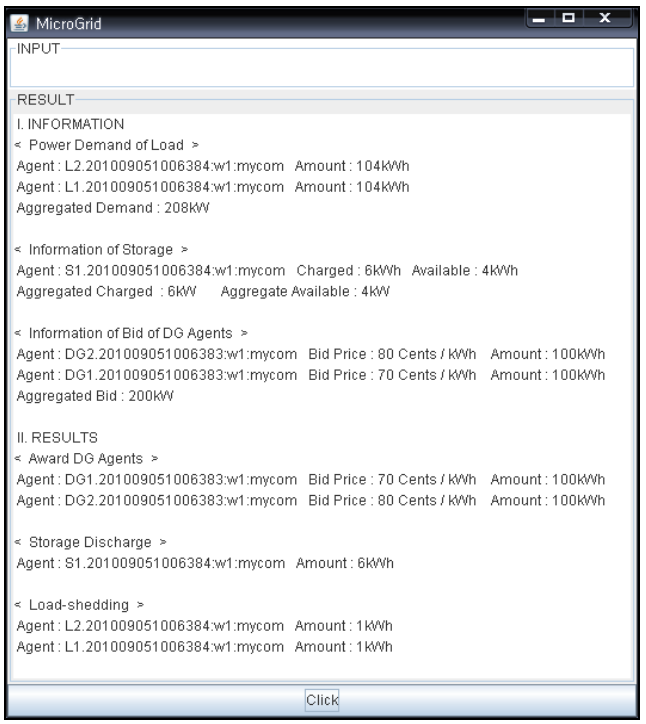
(**B**)



(**C**)



(**D**)



5.5. Case 5—Operation of Supply Surplus Required Additional Decrease of Generation

A supply surplus of 110 kW occurs in this case. To meet the power balance between supply and demand for operation of the next interval, the supply surplus should be solved. We check whether charge of a storage device and the decrease of DGs are reasonably decided to solve the supply surplus.

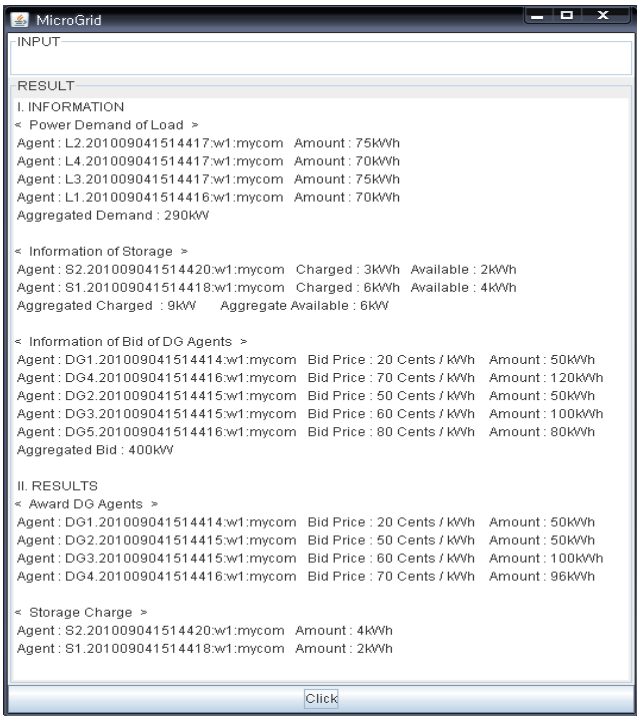
Figure 11A shows the result of Case 5. As you can see the result, DG 5 is not selected as a final supplier because of its high bidding price and the output of DG 4 is reduced. The result of DGs shows that the merit order works well. Also, storage devices, S1 and S2, are fully charged.

5.6. Case 6—Operation of Supply Shortage Required Load-Shedding

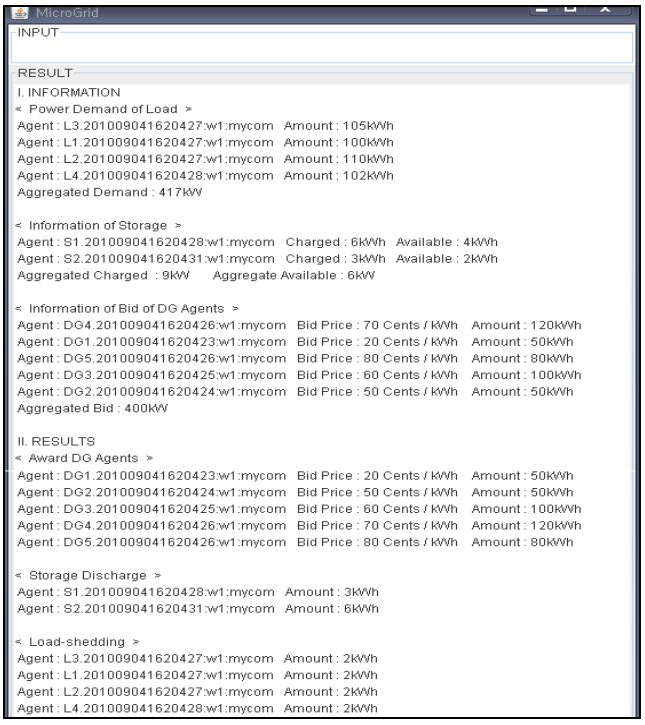
A supply shortage of 17 kW occurs in this case. To meet the power balance between supply and demand for operation of the next interval, the supply shortage should be solved. In this case, we check whether discharge of a storage device and additional load-shedding are effectively decided to solve the supply shortage. Figure 11B shows the result of Case 6. As you can see the result, storage devices are fully discharged and load-shedding is allocated to all loads to solve the situation of supply shortage.

Figure 11. Result of (**A**) Case 5; (**B**) Case 6.

(**A**)



(**B**)



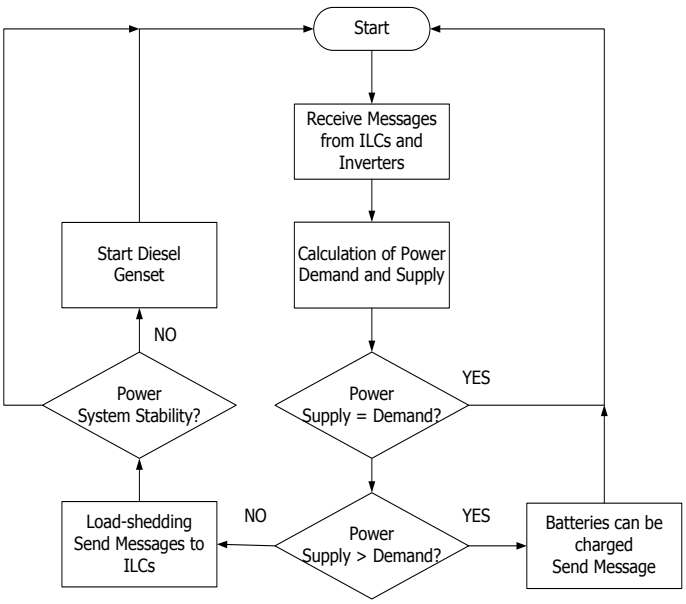
5.7. Evaluation and Discussion

We carried out tests on six operation conditions to show the functionality and feasibility of the suggested multiagent system. Through six tests, we checked that an islanded microgrid is operated autonomously as well as appropriately to design purposes by the suggested multiagent system.

There are some specific features of the suggested multiagent system compared with previous ones: works [11–14] as follows:

- The proposed multiagent system is based on the CNP as well as an IEP. Especially, we think that the CNP used for interactions between the MGOCC agent and DGs agents is a good choice because their interactions are suitable to the following steps of the CNP [27,30]:
  - Step 1: A manager announces the existence of a task via a broadcast message;
  - Step 2: Agents evaluate the announcement and some of these agents having the solving capability against the task submit a bid;
  - Step 3: The manager awards a contract to the most suitable agent among candidate agents as a contractor for that task.
- In the multiagent system for an islanded microgrid in reference [12], the MGCC algorithm looks like to our cooperative operation scheme, but there are the following differences: the main objective in their application is the minimization of the use of the diesel generator and therefore, a diesel generator is used after deciding load-shedding, as shown in Figure 12 [12]. In addition, batteries can be used only in the case of supply shortages. Therefore, the main ideas are different from our scheme based on the minimization of load-shedding as shown in Figure 3.
- To select final DGs as suppliers, the merit order algorithm is used in this paper. Since the merit order algorithm is a widely used algorithm, the reliability of our scheme is guaranteed and also, it has the merit of being simple yet practical.
- Especially, in our approach, the CEA is used to distribute load-shedding to loads. Since load-shedding is a critical problem, the CEA application can be considered a reasonable method. Also, there is an additional merit in that the CEA guarantees a unique solution in the bankruptcy problem [31]. In our additional test, we checked that it took about 270 msec to solve the load-shedding problem with 100 loads. Therefore, it is considered that using the computation time of the CEA is enough for real microgrid applications.

Figure 12. Flow chart of the MGCC algorithm [12].



In our multiagent system, the MGOCC agent has important functions such as deciding final suppliers, load-shedding, action of storage devices. It resulted from the fact that to meet a power balance between supply and demand in the islanded mode of the microgrid is a critical problem and is more difficult to solve it than in the grid-connected mode. For this reason, the MGOCC agent of our multiagent system, like the MGCC agent in reference [12], has many important functions.

In real applications, we think that the use of short interval period is more effective to reduce the uncertain factors in Section 1. We checked that it took only a few seconds for the processing time of an interval in our tests. Finally, we anticipate that our multiagent system can manage and control the conventional software modules and functional devices for microgrid operations easily by the wrapping mechanism mentioned in Section 4.

6. Conclusions

In this paper, we have presented a multiagent system for autonomous operation of an islanded microgrid based on a cooperative operation scheme in a power market environment. We have built a multiagent system for autonomous operation of the islanded microgrid on the ADIPS/DASH framework. To verify the functionality and feasibility of the suggested multiagent system, we carried out six tests under four operation conditions. The results of the tests agreed with our design purpose. As future work, we plan to study multiagent-based microgrid operation, including thermal energy and agent-based protection of microgrids.

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