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# A New Modified CNP for Autonomous Microgrid Operation Based on Multiagent System

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**Abstract -** This paper presents a new modified Contract Net Protocol (CNP) for microgrid operation based on multiagent system. The CNP is a widely used protocol for interactions among distributed problem solving. The Contract Net Interaction Protocol of the Foundation for Intelligent Physical Agents (FIPA-CNIP) is a minor modification of the original CNP for multiagent system applications. In this paper, a modified CNP (MCNP) based on the FIPA-CNIP is proposed for more specialized interactions among agents for microgrid operation. A multiagent system is designed and constructed for microgrid operation. A microgrid operation based on the multiagent system is tested to check the functionality of the proposed MCNP.

**Keywords:** Microgrid, Multiagent system, A modified contract net protocol (MCNP), Agent-based microgrid operation

## 1. Introduction

Microgrid has recently received increasing attention. The main energy sources of microgrid are renewable energy sources such as solar and wind power and small-scale combined heat and power (CHP) facilities based on fuel cells and micro-turbines. Particularly, the energy sources of the microgrid are related to climate change as clean energy sources, making the microgrid a good option for popularizing the sources into power grids. For this reason, a number of projects for developing and demonstrating microgrids have been carried out in many countries [1], [2].

A remarkable change in the area of power engineering is its fusion with information technology (IT), the product of which is the smart grid technology. This technology has been faced many challenges for successful applications. One example is the application of the agent technology, which is under IT, because an agent's characteristics of reactivity, pro-activeness, and social ability can cause power grids to be more autonomous and smarter [3]-[5]. Against this backdrop, agent-based microgrid - as well as other agent applications - has been studied in the field of power engineering [6]-[8].

The Contract Net Protocol (CNP) is one of the most widely used protocols for distributed problem solving [9]. The CNP was proposed by R. G. Smith in 1980 for solving the cooperative distributed problem in communications [10]. One of its salient features is its simple framework based on announcing a new task, bidding, and awarding a contract. The basic steps of the CNP are similar to the steps of dealing a contract in the human society. The original CNP has been modified for particular applications and for effective uses in many application areas [11]-[13]. The Foundation for Intelligent Physical Agents (FIPA) recommended the Contract Net Interaction Protocol (CNIP) as a modified version of the original CNP for agents' communications [14].

In this paper, we propose a modified CNP (MCNP) for microgrid operation. In the MCNP, which is based on the FIPA-CNIP, the "propose" of the FIPA-CNIP is departmentalized to "propose-supply" or "propose-load" according to the difference in the roles of a supplier and a consumer of power. Three tasks related to generators, loads, and storage devices, are performed concurrently in the MCNP. Particularly, a task related to storage devices is performed after checking a power balance between supply and demand from the other two ongoing tasks for a kind of cooperative microgrid operation.

In Section 2, backgrounds relating to microgrid operation, the multiagent system, and the CNP are described. The proposed MCNP is explained in detail in Section 3. In Section 4, a multiagent system for microgrid operation is designed and constructed for tests. The multiagent system is tested in order to check the functionality of the proposed MCNP for microgrid operation in Section 5. In Section 6, we conclude.

## 2. Background

### 2.1 Microgrid Operation

Microgrid is a private small-scale power grid. Fig. 1 shows its typical configuration, which is composed of distributed generation systems (DGs), distributed storage devices (DSs), and loads, where PCC is an abbreviation for

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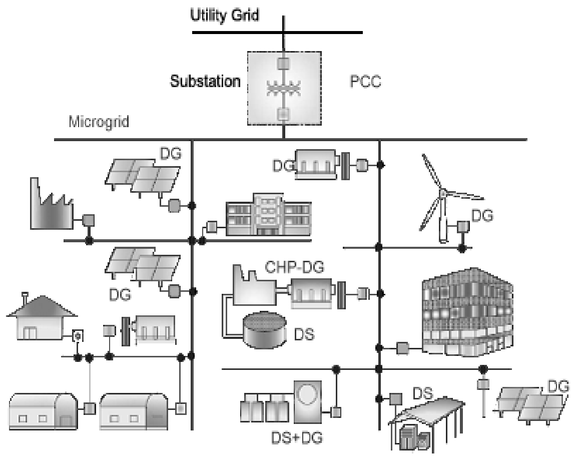


**Fig. 1.** Typical configuration of microgrids [15].

the point of common coupling [15].

Microgrid is operated by the following two modes:

a) Grid-connected mode: A microgrid is connected to a power grid. In this mode, the microgrid controls a power balance between supply and demand using power trade with the power grid to keep a constant frequency, e.g., 60 or 50 Hz.
b) Islanded mode: A microgrid is isolated to a power grid. In this mode, the microgrid controls the power balance using regulation of generation and load to keep a constant frequency whenever an imbalance occurs.

In this paper, we focus on the grid-connected mode and on establishing an operation plan for the next interval. We assume that the Microgrid Operation and Control Center (MGOCC) has information on buying price ($P_B$) and selling price ($P_S$) for trading power with the power grid for the next interval, where $P_B \geq P_S$ which is the same as the case of a general market. The MGOCC takes part in operation as a manager. In the case of supply excess, the MGOCC selects final suppliers with the merit order algorithm. A supplier bids the amount of supply with a bidding price, which is his/her production cost. A supplier that was refused or partly selected from selecting final suppliers by the MGOCC can trade his/her power to the power grid. The details mentioned above were explained in our previous work [7].

### 2.2 Multiagent System

An agent or an artificial software agent has the following capabilities: reactivity, pro-activeness, and social ability, and so on. A multiagent system is composed of multiple autonomous agents; agents control their local systems using interactions, communications, and knowledge sharing among agents against changes in their environments according to their design purposes. They sometimes cooperate for a common profit and sometimes compete for their profits [9], [16].

### 2.3 CNP

The CNP was proposed for a high-level protocol for communication and control in a distributed problem solver by R.G. Smith in 1980 [10]. It has also been used as the most implemented and extensively studied framework for distributed problem solving in spite of simplicity [9]. Fig. 2 shows the basic steps of the original CNP [16].

The FIPA recommends the FIPA-CNIP as a modified version of the original CNP. The big differences between the original CNP and the FIPA-CNIP are as follows [14]:

a) The rejection of a proposal is added to the FIPA-CNIP.
b) In the FIPA-CNIP, the participant sends a completion message to the initiator in the form of an inform-done or a more explanatory version in the form of an inform-result once the participant has completed the task. However, if the participant fails to complete the task, a failure message is sent.

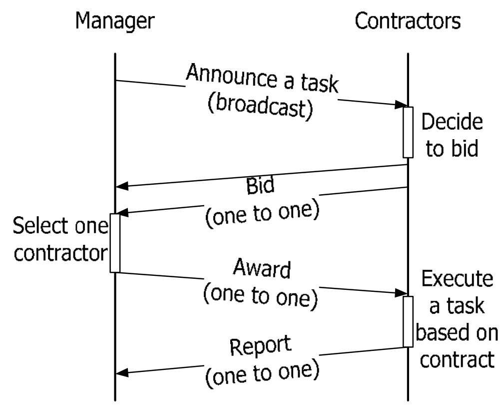


**Fig. 2.** CNP for a task.

## 3. MCNP for Microgrid Operation

### 3.1 Interactions among Agents

A multiagent system for autonomous microgrid operation is defined as follows:

$$Ag = \{Ag_{\mathrm{MGOCC}}, AG_{\mathrm{DG}}, AG_{\mathrm{DS}}, AG_{\mathrm{L}}\} \quad (1)$$

where $Ag_{MGOCC}$ is the MGOCC agent, which is a manager agent of the CNP; $AG_L$ is a set of load agents ($Ag_L$); $AG_{DG}$ is a set of DG agents ($Ag_{DG}$); and $AG_{DS}$ is a set of storage device agents ($Ag_{DS}$).

Table 1 shows the basic interactions among agents for microgrid operation, where $AG_{DS}$ has two roles - as a consumer and as a supplier - according to the charge and discharge actions of the DS.

**Table 1.** Interactions among agents

| Agents | Interactions |
|---|---|
| Between $Ag_{MGOCC}$ and $AG_{DG}$ | • $Ag_{MGOCC}$ requires a bid for power supply to $AG_{DG}$ with trading prices with the power grid<br>• $AG_{DG}$ bids with supply price and amount to $Ag_{MGOCC}$<br>• $Ag_{MGOCC}$ awards a contract to $AG_{DG}$ as a final supplier<br>• $AG_{DG}$ sends a report of the contract to $Ag_{MGOCC}$ after finishing the contract as a final supplier |
| Between $Ag_{MGOCC}$ and $AG_{L}$ | • $Ag_{MGOCC}$ requires information of load to $AG_{L}$ with power trading prices with power grid<br>• $AG_{DG}$ informs his/her load to $Ag_{MGOCC}$ |
| Between $Ag_{MGOCC}$ and $AG_{DS}$ | • $Ag_{MGOCC}$ requires bid for supply task with power trading prices with power grid or power for charge action to $AG_{DG}$<br>• $AG_{DS}$ bids with supply price and amount or informs the power amount required for charge action to $Ag_{MGOCC}$<br>• $Ag_{MGOCC}$ awards a contract to $AG_{DS}$ as a final supplier in the case of a supplier<br>• $AG_{DG}$ sends a report of the contract to $Ag_{MGOCC}$ after finishing the contract as a final supplier |

### 3.2 Basic Process of MCNP

In this paper, we propose the MCNP for interactions among agents for microgrid operation, in which three concurrent tasks between the MGOCC and participants have to be dealt with - DGs, DSs, and loads. Hence, the basic process of the MCNP is designed by extending the FIPA-CNIP. Fig. 3 shows the MCNP for a task of microgrid operation, where deadlines are shown in Fig. 4. In particular, the result of each task is reported within $t_4$ after interval t+1.

There is a big difference between the FIPA-CNIP and the proposed MCNP for microgrid, which lies in the segmentation of the "propose" message of participants, such as DG agents, load agents, and DS agents in the protocol. The segmentation was cause by the difference of a message sent between suppliers and consumers because the former bid their supply with bidding prices and the latter inform their load. In the case of DS agents having two roles, they can select "propose-supply" or "propose-load" according to their action.

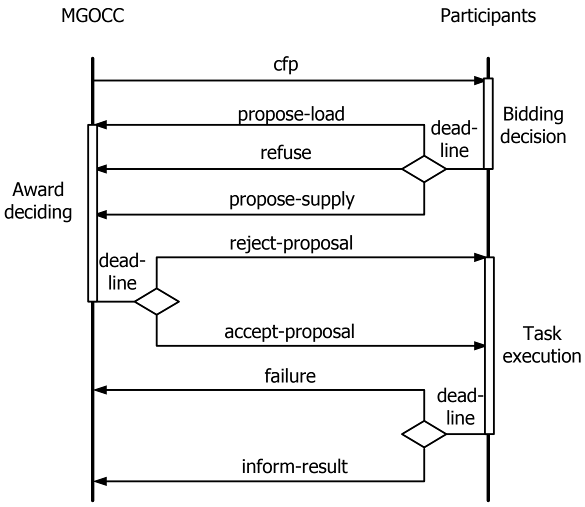


**Fig. 3.** MCNP for a task of microgrid operation.

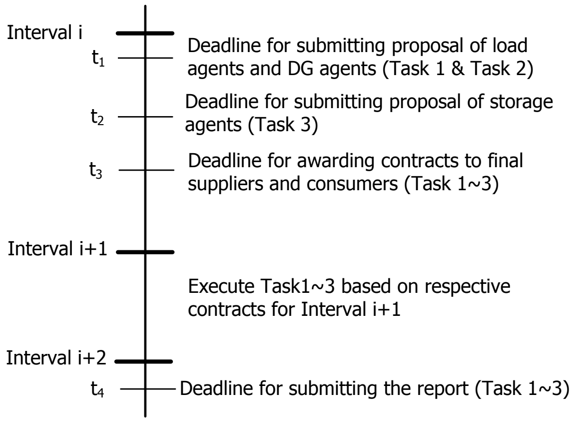


**Fig. 4.** Deadlines of MCNP.

### 3.3 Microgrid Operation Based on MCNP

Three tasks are concurrently performed in the MCNP, as shown in Fig. 5. Task 1 is a task for load agents, task 2 for DG agents, and task 3 for DS agents. Especially in the case of task 3, the MGOCC announces a new task to DS agents with information including the status of a power balance after checking the power balance. This mechanism helps

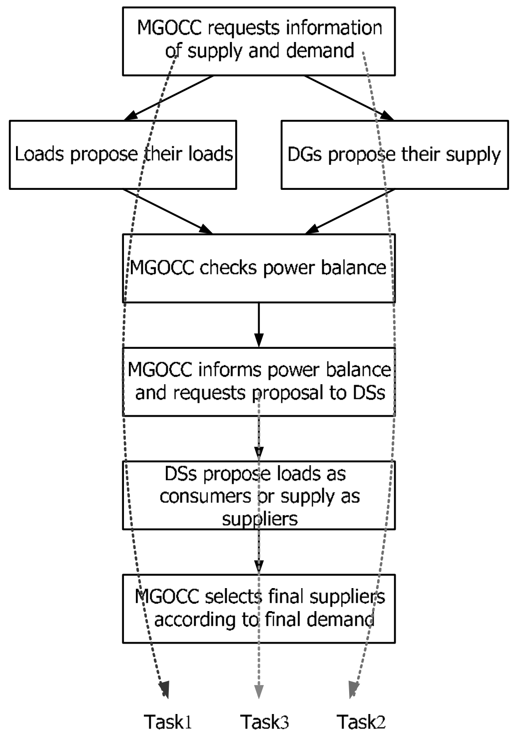


**Fig. 5.** Three tasks based on the MCNP.

**Table 2.** Performatives for MCNP

| Performative | Meaning |
|---|---|
| cfp | • Call for proposal with information of bidding prices<br>• For DSs, information of the power balance is added (–1: supply shortage; 1: supply excess) |
| Propose-supply | • Propose supply amount with the price |
| Propose-load | • Inform load amount |
| Refuse | • Refuse proposal on unavailable service condition |
| Accept-proposal | • Accept participation and inform final supply amount or load amount |
| Reject-proposal | • Reject participant (especially DGs and storage devices) |
| Failure | • Inform failure of implementation of the contract |
| Inform-result | • Inform to finish the contract with details |

DG agents to effectively make decision on charge or discharge. This is related to a characteristic of cooperative operation.

Table 2 shows the performatives designed in the MCNP for microgrid operation. In the case of call for propose (cfp), there is additional information for the DS as mentioned above. DS can select one between “propose-supply” as a supplier and “propose-load” as a consumer as mentioned above.

In this paper, a modified version of Knowledge Query and Manipulation Language (KQML) was used as an Agent Communication Language (ACL). The following message shows an example used for bidding supply from DGs, where “?xx” is a variable for a character string:

[Msg :performative propose-supply :to ?to :content (m_propose_supply :from ?my_name :amount ?supply_amount :price ?supply_price :interval ?interval)]

Fig. 6 shows the overall behavior of agents based on the MCNP, where the number in a circle is the deadline mentioned in Fig. 4.

## 4. Building an Experimental Multiagent System Based on the MCNP

### 4.1 Design of Microgrid Agents

Fig. 7 shows the workflow of the MGOCC agent as a manager of the MCNP. The workflow is designed to concurrently deal with three tasks of the microgrid operation based on the proposed MCNP. For selecting final suppliers, the MGOCC agent uses the merit order algorithm [7],[17], where the number of multiple suppliers with the highest bidding prices is proportionally divided according to their bidding amount. Messages of call for proposal are sent to every agent using a broadcast message.

For the decision making of bidding, DG agents use the following bid function, *F*(*bid*) [7];

$$F(bid) = \begin{cases} 1 & if\ P_{cost} \le P_B \\ 0 & other \end{cases}, \tag{2}$$

where $P_{cost}$ is the production cost, which is used as a bidding price in this study, and $P_B$ is a buying price from the power grid.

For the decision making of trading with the power grid, the following decision-making function, *F*(*trade)*, is used for the DG agent that was refused or partly selected by the MGOCC:

$$F(trade) = \begin{cases} 1 & if\ P_{cost} \le P_S \\ 0 & other \end{cases}, \tag{3}$$

where $P_S$ is a selling price from the power grid.

DS agents use the information of a power balance received from the MGOCC agent to decide their charge or discharge action. In this paper, DS agents use a simple decision-making strategy to check the functionality of the proposed MCNP as follows:

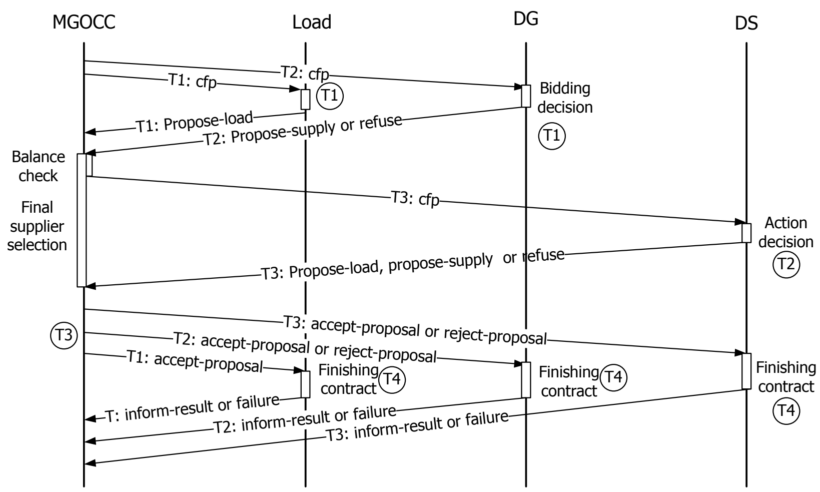


**Fig. 6.** Behavior of agents based on the MCNP.

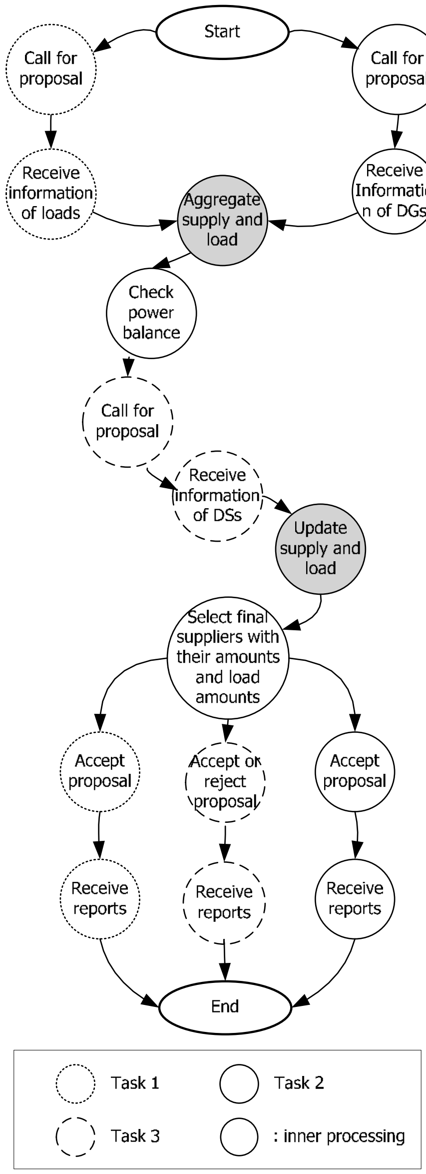


**Fig. 7.** Workflow of the MGOCC agent.

a) DS agents as suppliers bid the full charged amount using (2), where their bidding prices are updated by the arithmetical mean considering the charged amount and the electricity charge shown in (4) whenever charge action occurs

b) DS agents as consumers charge the full available amount or the difference between the maximal capacity and state of charge (SOC).

The electricity charge ($Char_{MG}$) for consumers is assumed as follows:

$$Char_{MG} = \frac{\max(P_S, P_{HB}) * \sum P_{Bid} + P_B * P_{PG}}{\sum P_{Bid} + P_{PG}} \quad (4)$$

where $\max(P_S, P_{HB})$ is the maximum price between $P_S$ and the highest bidding price of final suppliers ($P_{HB}$); $\Sigma P_{Bid}$ is the total amount supplied by final suppliers; and $P_{PG}$ is the amount bought from the power grid.

Every agent has a function of alarm for indicating deadlines for their schedule control. A state function ($F$) is used for effective task management as follows:

$$(s', a) = F(s, e), \quad (5)$$

where s', a, s, and e refer to the new state, the action, the current state, and the event, respectively.

### 4.2 Implementation

The experimental multiagent system is constructed using Distributed Agent System based on Hybrid Architecture (DASH) as a multiagent platform, Interactive Design Environment for Agent Designing Framework (IDEA) as a GUI-based interactive environment for the DASH platform, and Java for user defined functions [7], [19]-[21].

## 5. Experiment

### 5.1 Experimental Multiagent-based Microgrid

Fig. 8 shows an experimental multiagent-based microgrid to test the functionality and feasibility of the proposed MCNP in microgrid operation. The multiagent system for the microgrid is composed of the MGOCC agent ($Ag_{MGOCC}$), two DG agents ($Ag_{DG1}$ and $Ag_{DG2}$), a DS agent ($Ag_{DS1}$), and two load agents ($Ag_{L1}$ and $Ag_{L2}$).

The details of DG1, DG2, and DS1 are as follows:

- DG1 = production cost: 40 ¢/kWh; capacity: 15 kWh
- DG2 = production cost: 70 ¢/kWh; capacity: 25 kWh
- DS1 = initial charge: 0 kWh; initial cost: 0 ¢/kWh; capacity: 5 kWh

Table 3 shows the details of L1, L2, and trading prices ($P_B$ and $P_S$) of the intervals, where eight intervals are considered.

A variable length of the interval was considered within 20 seconds to check the processing time for microgrid op-

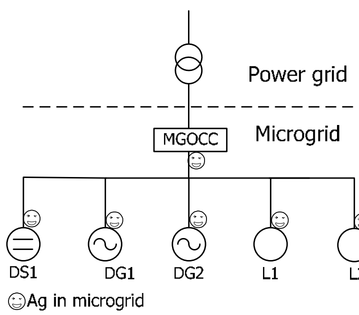


**Fig. 8.** Experimental multiagent-based microgrid.

**Table 3.** Loads and trading prices

| Interval | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| L1 kWh | 15 | 17 | 15 | 18 | 20 | 15 | 17 | 15 |
| L2 kWh | 20 | 24 | 22 | 22 | 25 | 20 | 19 | 20 |
| $P_B$ ¢/kWh | 90 | 98 | 93 | 98 | 102 | 93 | 97 | 90 |
| $P_S$ ¢/kWh | 64 | 70 | 66 | 70 | 74 | 66 | 70 | 64 |

eration based on the MCNP. Deadlines in Fig. 4 are as follows:

- T1 = 2 seconds after receiving the call for proposal
- T2 = 2 seconds after receiving the call for proposal
- T3 = 2 seconds after deciding the final contractors
- T4 = 2 seconds after finishing the contract

Points considered in this experiment are as follows:

a) Whether the microgrid operation is automatically and autonomously performed by the experimental multi-agent system
b) Whether the proposed MCNP works in design intension for interactions among agents

### 5.2 Results of Experiment

Fig. 9 shows the results of the DS agent as consumers. In intervals 1, 3, and 6, DS1 plays the role of a consumer by charge action because supply surplus occurs in these intervals and DS1 has the available volume for charge.

Fig. 10 shows the results of the DS agent as suppliers. In intervals 2 and 5, DS1 discharges electricity as a supplier because supply shortage occurs in these intervals and DS1 has the charged amount for discharge.

Fig. 11 shows the results of power trade with the power grid. In intervals 2 and 7, DG2 sells surplus power to the power grid. On the other hand, the microgrid purchases shortage power from the power grid in interval 3.

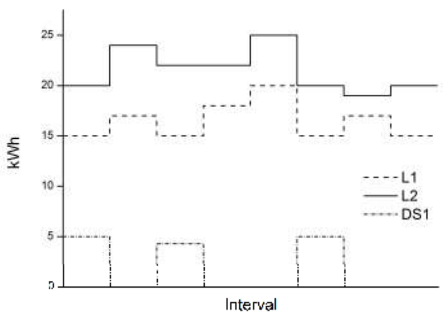


**Fig. 9.** Results of DS agent as a consumer.

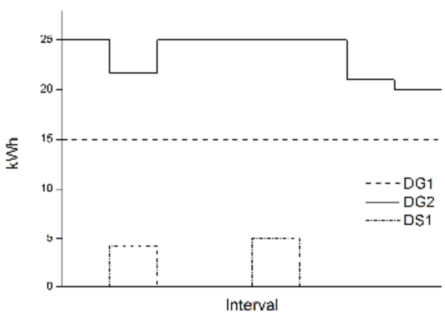


**Fig. 10.** Results of DS agent as a supplier.

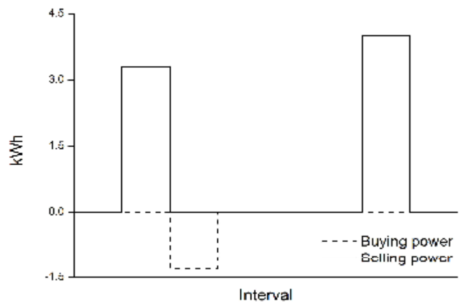


**Fig. 11.** Results of power trade with power grid.

### 5.3 Evaluation of MCNP

Fig. 12 shows a part of a window for showing the results of microgrid operation in interval 2 and a part of the log data recorded by the MGOCC agent. The results of suppli-

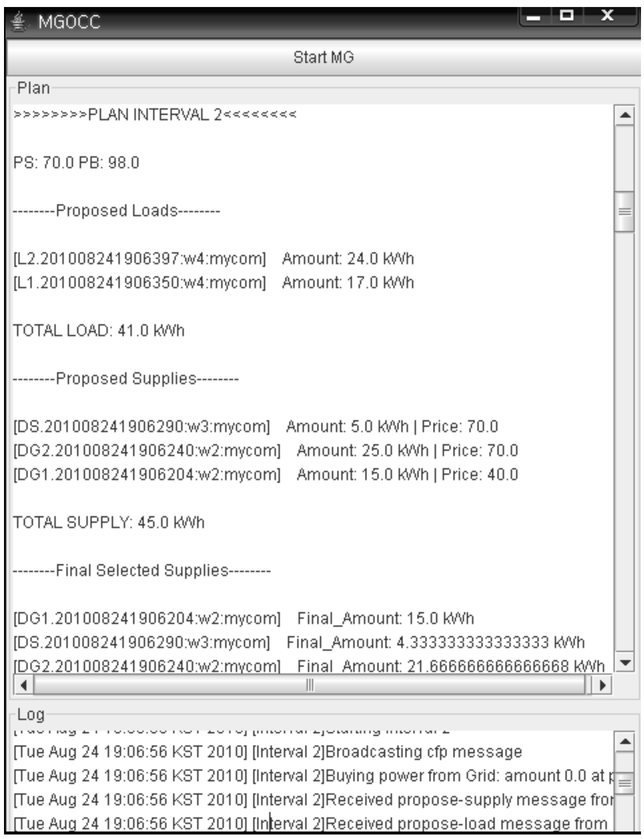


**Fig. 12.** A window showing the results of microgrid operation and log data recorded by the MGOCC agent.

ers' bids and the final selection by the merit order algorithm are shown in the figure. As can be seen, the amount of final supply of DG2 and DS1 is proportionally divided according to their bidding amount because their bidding prices are the same as those mentioned in sec. 4.1.

Fig. 13 shows a part of the log data recorded by the MGOCC in interval 2. The last part of the figure shows concurrent process of the new task of interval 3 and the suppliers' report of interval 1. As can be seen, the MCNP works well. The average processing time of each interval is measured to be 12 seconds through eight intervals.

The following were derived from the results of the tests:

a) The proposed MCNP works well for microgrid operation based on the multiagent system in design intension.
b) The detailed functions mentioned in section 4.1 works well.
c) Microgrid operation is automatically and autonomously performed by the experimental multiagent system.

```
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Broadcasting cfp
message
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Buying power from
Grid: amount 0.0 at price 90.0
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Received propose
-supply message from DG1.201008241906204:w2:mycom
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Received propose
-load message from L1.201008241906350:w4:mycom
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Received propose
-supply message from DG2.201008241906240:w2:mycom
[Tue Aug 24 19:06:56 KST 2010] [Interval 2]Received propose
-load message from L2.201008241906397:w4:mycom
[Tue Aug 24 19:06:58 KST 2010] [Interval 2]Received propose
-supply message from DS.201008241906290:w3:mycom
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Propose deadline
timeout. Making decision...
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Sending accept-
proposal message to DG1.201008241906204:w2:mycom
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Sending accept-
proposal message to DS.201008241906290:w3:mycom
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Sending accept-
proposal message to DG2.201008241906240:w2:mycom
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Sending accept-
proposal message to L2.201008241906397:w4:mycom
[Tue Aug 24 19:07:00 KST 2010] [Interval 2]Sending accept-
proposal message to L1.201008241906350:w4:mycom
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Starting interval
3
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Broadcasting cfp
message
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Received propose
-load message from L2.201008241906397:w4:mycom
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Received Report
from DS.201008241906290:w3:mycomof Interval 1: bought Amount
5.0 at Price 70.0
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Received Report
from DG1.201008241906204:w2:mycomof Interval 1: sell_to_mg
Amount 15.0 at Price 70.0
[Tue Aug 24 19:07:08 KST 2010] [Interval 3]Received propose
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**Fig. 13.** Results of power trade with power grid.

There is room for improvement for more effective decision-making strategies and algorithms of the experimental multiagent system. In this paper, we focused on the feasibility, as well as the functionality, of the MCNP for microgrid operation based on the multiagent system. Test results were satisfactory.

To test our proposed MCNP, we assumed several operational rules for microgrid operation in this paper. However, the MCNP-based multiagent system for microgrid operation is not restricted to these rules because the software-based multiagent system has design flexibility according to operational rules.

## 6. Conclusion

In this paper, we proposed an MCNP for microgrid operation, taking into consideration the specific features of microgrid operation. A multiagent system was designed and implemented based on the MCNP. An experimental agent-based microgrid was tested to check the feasibility, as well as functionality, of the MCNP. The experiment was successfully tested.

In this paper, a simple decision-making strategy was used to check the action of DS. As future work, we plan to study an effective strategy for the decision making of DG.

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