

Distributed Intelligent Microgrid Control Using Multi-Agent Systems

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Received 2013

ABSTRACT

In the future, the individual entities of microgrids such as distributed generators and smart loads may need to determine their power generation or consumption in more economic ways. Intelligent agents can help the decision-making procedure of the entities by intelligent algorithms and state-of-the-art communication with central controller and other local agents. This paper presents the development of a table-top microgrid control system using multi-agent systems and also the demonstration of demand response programs during power shortage. In our table-top system, agents are implemented using microcontrollers and Zigbee wireless communication technology is applied for efficient data communication in the multi-agent system. The power system models of distributed generators and loads are implemented in the real-time simulator using Opal-RT system. The whole test system that includes real-time system simulation and agent hardware is implemented in the hardware-in-the-loop simulation framework. The performance of the developed system is tested for emergency demand response cases.

Keywords: Microgrid; Multi-agent System; Energy Management System; Hardware-in-the-Loop Simulation

1. Introduction

Microgrids have recently emerged as a new paradigm for the future power distribution system that can host multiple distributed energy resources (DERs) in the local distribution system levels. Microgrids can also be designed as autonomous independent cells in power grids because they can control the net power flowing into and out-of the microgrids to the pre-determined values or contracts. Therefore, microgrids can improve flexibility of power grid operation [1-3].

In addition, many electricity customers need to cut the cost of their electricity bill by applying smart information technology. Conventional centralized microgrid management systems have advantages to effectively manipulate the power generation or consumption of the whole microgrid but it is difficult to consider delicate request of individual entities such as DERs and local loads, especially in terms of economic concerns. On the other hand, multi-agent systems (MASs) have more interest in individual entities by nature. The agents can obtain information by measuring local parameters and communicating with other agents spontaneously. The agent can make a decision with artificial intelligence by negotiating and cooperating with other agents [4-8].

This paper presents the implementation of the table-top system of MAS-based microgrid system. The micro-

grid model contains a battery energy storage system (BESS), a micro-gas turbine (MGT), and a smart load. Intelligent agents are implemented using AVR ATmega 128 microcontrollers. The microgrid simulation model and the agent hardware are interfaced via hardware-in-the-loop simulation (HILS) setup. The control signals of DERs or loads are determined by the corresponding agents. The control command is delivered from the agents to the DERs and loads in the simulation via analog and digital I/O port of the Opal-RT system. The communication between agents uses Zigbee wireless communication protocol, which is a low-cost, low-power, and wireless mesh network standard. Therefore, agents can communicate with other agents by using either peer-to-peer or one-to-many communication mode.

When the grid power reserve diminishes quickly, the grid operator needs emergent load reduction for stable operation. This procedure is called as demand response. One of the popular demand response programs is emergency demand response (EDR) that offers incentives to the customers who instantly reduce their load [9]. In this paper, the control objective of the MAS-based microgrid control is to find the optimal condition for EDR.

Detailed decision-making procedure based on MAS configuration is presented in this paper and the performance of the control scheme is verified by the HILS experiments.

2. MAS-Based Microgrid Control

2.1. Microgrid System Model

Figure 1 illustrates a single-line diagram of a microgrid that contains a BESS, a MGT, and a smart load that used in this paper.

Integration of a BESS into microgrids can compensate instant power mismatch introduced by renewable energy resources or load variation. **Figure 2** illustrates the equivalent model the BESS that contains a Li-ion battery model, a bi-directional dc-dc converter, and a three-phase inverter. This paper used the battery model provided by MATLAB/Simulink. The non-isolated bi-directional boost converter has continuous current waveform so the battery can have long life span. If there is no external control input, the charging and discharging modes are determined by the level of the SOC of the battery because the SOC should be maintained between 30% and 80% during the normal state. If the SOC is lower than 30%, the BESS charging control starts.

The MGT is modeled by equivalent synchronous generator and an AC/DC rectifier and DC/AC 3-level power inverter as illustrated in **Figure 3**. The rated power of the MGT is 30kVA and the inverter operates in constant power control mode. The smart load model employs a current-controlled converter so that the load operates as a constant-current load. In this paper assumes that the smart load consists of controllable load and fixed load.

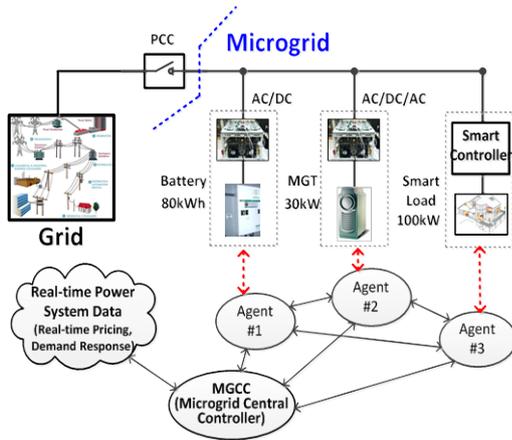


Figure 1. Configuration of microgrid with MAS-based control system.

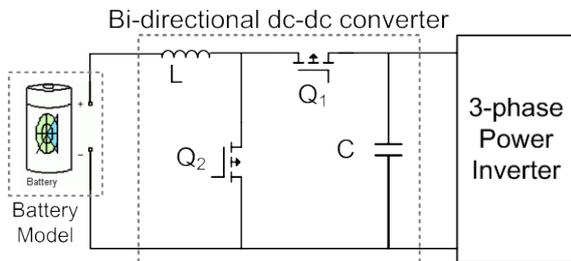


Figure 2. Configuration of BESS.

2.2. Multi-Agent System

Figure 1 also shows the concept of MAS-based microgrid control system. Each intelligent agent takes charge of decision-making for a DER or a smart load.

Intelligent agents have reactive, proactive, and social abilities so that they can react to the environmental changes, follow the final goal, and interact between other agents in a cooperative or competitive manner [4]. Reference [5] explains that agent should have fundamental modules such as data collection, communication, decision-making, action implementation, and knowledge management.

Coordination of multiple intelligent agents is an important issue. In the developed control system, the Microgrid Central Coordinator (MGCC) coordinates multiple intelligent agents. When a special control request arrives from the main grid such as emergency demand responses, the MGCC informs agents of the control objectives for the whole microgrid. After receiving the individual proposal of the agents, the MGCC dispatches the control command to the agents.

The overall decision-making procedure follows the Contract Net Protocol (CNP) [10]. The CNP provides a formal procedure in the coordination procedure in MAS-based management systems. The contract between the MGCC and the agents can be reached by the process of decision-making and interaction based on two-way communication. **Figure 5** illustrates the concept of the CNP based decision-making procedure. The overall procedure starts when the main grid requests for certain actions such as demand response.

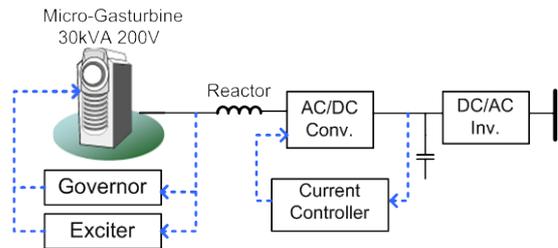


Figure 3. Configuration of MGT.

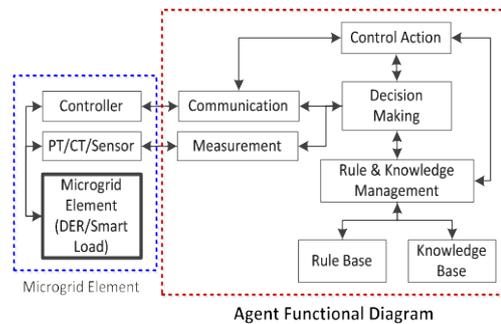


Figure 4. Functional diagram of agents

In the CNP procedure, decision-making processes can be found both in the MGCC and the agent side. Agents make a decision such as how much it will participate in the present task requested by the MGCC. To approach an optimal solution, the agents evaluate the detailed conditions of the task and check local information such as generation cost, state-of-charge of a battery, energy market price, and so on. Agents can use artificial intelligent algorithms such as knowledge-based expert system, fuzzy systems, or neural networks to attain maximum benefits from the task. The MGCC decides the overall operation scheme for a microgrid after receiving the bids from the agents. If the bids from the agents are not enough to meet the request from the grid, the MGCC can modify the task conditions to lead additional participation from the agents.

3. Hardware-in-the-Loop Simulation

3.1. Real-Time Simulation

The microgrid dynamic simulation model is implemented using RT-LABTM software in Opal-RT simulation environments. RT-LAB is designed to realize the real-time simulation of Simulink models on clusters of standard multi-core CPU computers. RT-LAB builds parallel tasks from the original Simulink model and then assigns each task on one CPU of the multi-core computer so that the overall simulation can be accelerated. The simulation time and accuracy of the microgrid can also be improved by using power system solver and toolboxes of RT-LAB. **Figure 6** shows the real-time simulation model and Opal-RT system.

3.2. Agent Hardware

There are three agents in our HIL simulation setup: two for the DERs, MGT and BESS, and one for the smart load. The DER agents obtain the information such as current output power, rated power, battery SOC and so forth and determine the output power reference based on its own operation strategies considering cost, power margins and so on.

Figure 7 shows the hardware of the agent for the BESS. The agent hardware consists of a main control board, a Zigbee module, a digital-to-analog converter, and a LCD display module. The main control board of the agent uses an AVR ATmega128 microcontroller that is commonly used in industrial embedded system applications. The microcontroller collects various data through built-in devices such as analog-to-digital converters and serial communication ports of the ATmega128.

The agent can cooperate with other agents and the central coordinator if necessary. The information between agents and the coordinator can be transferred through

wireless communication based on ZigbeeTM protocol. Zigbee is one of the popular solutions for short-distance wireless personal area networks. Compared to other communication solutions, Zigbee is advantageous for short-distance sensor or controller networks such as residential or commercial applications because of security, low power consumption, and so on. Since there is no physical line connection between agents, the configuration of Zigbee-based MAS network and the cooperative operation procedure are flexible.

3.3. Microgrid Central Coordinator

The MGCC is defined as a central coordinator of a microgrid. The MGCC has three main functions: 1) to mine relevant data for microgrid operation from the power system, 2) to manage multiple agents and monitoring their status and 3) to coordinate agents to achieve the goal of the whole microgrid operation.

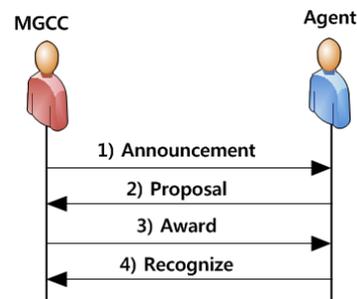


Figure 5. Concept of Contract Net Protocol between MGCC and agents.

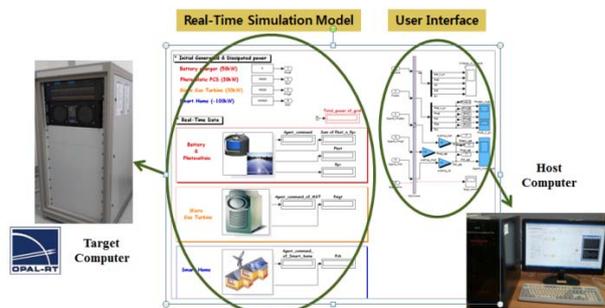


Figure 6. Real-time simulation model development using RT-LAB.

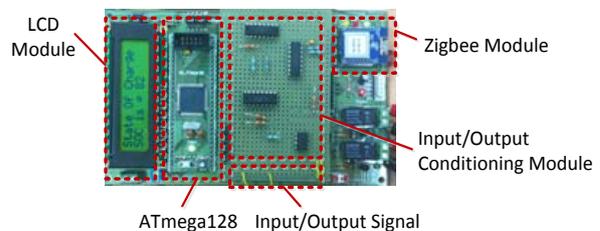


Figure 7. Agent hardware using AVR microcontroller with Zigbee module.

In this paper, the MGCC collects the real-time data such as electricity price and request for emergency demand response and incentives. When the MGCC receives a request for participation in demand response or power quality improvement, the MGCC determines whether the microgrid participates in the request or not. If the MGCC decides to join the request, the MGCC communicates with the agents in the microgrid to respond to the request optimally. The detailed protocol in the communication between the MGCC and the agents follows the Contract Net Protocol (CNP). **Figure 8** shows the screen of the MGCC GUI program.

3.4. Hardware-in-the-loop Simulations

Real-time simulation can be a powerful tool for power system studies. Especially, HILS provides means for the operation of physical hardware such as power components or control hardware while interfaced to a computer simulation of the system in which the physical hardware is intended to function. That is, HILS experiments allow for hardware device to be tested in a true-to-life test condition before the actual system is built and commissioned. It can also minimize the risk and cost to examine extreme conditions to identify hidden flaws before their impact manifests in actual operation.

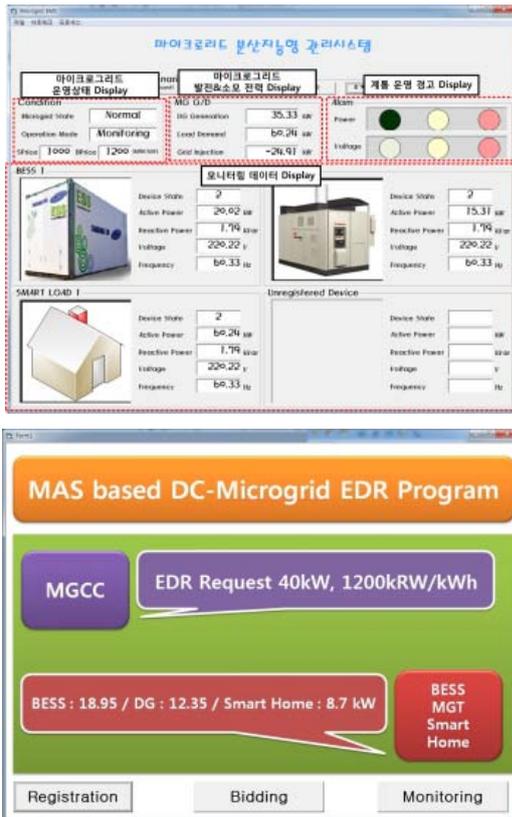


Figure 8. Screen capture of MGCC GUI program.

Figure 9 shows the configuration of the HILS setup for MAS-based intelligent microgrid control. The power system model of the microgrid is programmed with RT-LAB software installed in the host PC. The compiled simulation model in the host PC is downloaded in the Opal-RT system through Ethernet connection. Then, the microgrid model can run in the Opal-RT system in real time. **Figure 10** shows the actual line connections between the Opal-RT system and the agents. The agents communicate with other agents and the MGCC via Zig-beewireless communication. The MGCC is programmed in a laptop computer. The host PC is used for debugging the real-time model and monitoring the overall simulation system.

4. Demonstration

In this paper, the MAS-based microgrid control system is applied to the emergency demand response (EDR) program. In the EDR program, the grid operator pays significant incentives to the participants who can reduce their consumption. For example, in the US, the incentive money is about ten times higher than the electricity price

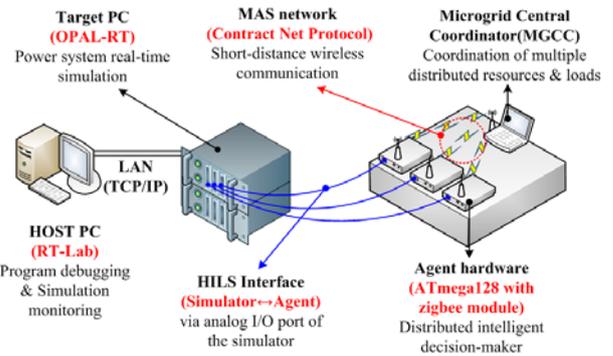


Figure 9. Configuration of HILS setup of MAS-based microgrid control.

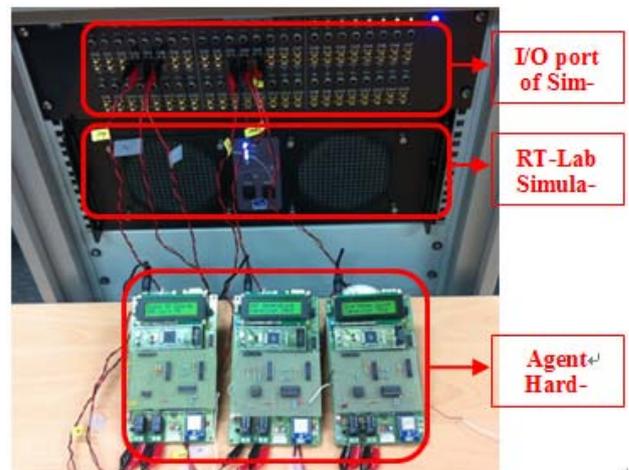


Figure 10. Interface between the Opal-RT and the agents

during the off-peak period [11]. The individual agents determine how much the corresponding DER or load will participate in the EDR program. To this end, the agents should determine their optimal values for power generation or consumption considering given conditions. The MGCC collects the bids from the agents and decides the power assignments of the agents by adjusting and coordinating conflicting bids.

As shown in **Figure 1**, the rated energy of BESS is 80kWh and the rated power of MGT, and smart load are 30kW and 100kW, respectively. Let us assume that the grid operator requests 40 kWh load reduction with the incentive as 1500 KRW/kWh. The initial operating conditions of the BESS and the MGT are as follows: the SOC of the BESS is 80%; the initial values of power generation of BESS and MGT are 20 kW and 15 kW, respectively. The initial state of smart load is 20kW of critical load which cannot be reduced.

Now, the MGCC informs the agents of the 40kWh EDR request with the incentive of 1200 KRW/kWh. Note that the incentive from the MGCC is 1200 KRW/kWh, which is less than the grid incentive 1500 KRW/kWh in the beginning.

The maximum participation power of the BESS can be defined as

$$P_{BESS}^{EDR} = \frac{Q_{rated}}{1hr} \times (SOC - SOC_{min}) - P_{BESS} \quad (1)$$

Where Q_{rated} is the rated capacity of the battery (kWh) that is 80 kWh, SOC is the current SOC; SOC_{min} is the minimum constraint of the SOC (%) that is set to 30%, and P_{BESS} is the initial power output of the BESS (kW), respectively. Then, the BESS can bid 20 kW for an hour due to

$$P_{BESS}^{EDR} = \frac{80kWh}{1hr} \times (80\% - 30\%) - 20kW = 20kW$$

The generation cost of gas-turbines can be represented as a quadratic function. The MGT agent must have the information about this cost function. The EDR participation power is determined when the marginal cost is the same as the incentive. Assume that the participation power of MGT is 10kW.

The smart loads consist of controllable loads that can be transferred to different time slots and critical loads that cannot be shed. If we assume that the initial critical and controllable loads are 20 kW and 40 kW respectively, the smart load can bid as much as 40 kW.

Then, in the first round, the MGCC receives the bids from the agents as much as 60 kW in total, which means 20 kW from the BESS, 20 kW from the MGT and 40 kW from the smart load. Then, the total EDR power participation is larger than 40kW of the request power. The MGCC dispatch the EDR participation proportionally

according the amount of bids as follows:

$$P_{EDR}^{(BESS)} = \frac{20}{20+20+40} \times 40kW = 10kW$$

$$P_{EDR}^{(MGT)} = \frac{20}{20+20+40} \times 40kW = 10kW$$

$$P_{EDR}^{(Load)} = \frac{40}{20+20+40} \times 40kW = 20kW$$

Figure 11 illustrates the decision-making procedure of the MGCC followed by the CNP framework. The MGCC can match the requested DR power with lower price than the original incentive offered by the grid operator. The balance money can be shared by the microgrid entities or can be used for microgrid maintenance cost.

If the sum of the bids from the agents is less than the EDR request from the grid, the MGCC increase the internal incentive a bit larger than 1200 KRW/kWh, say 1200 KRW/kWh. Then, agents may consider additional EDR participation. The MGCC checks if the total sum of the bids from agents matches with the grid request. If yes, the MGCC dispatch final participation power to the agents. Otherwise, the MGCC increase the internal incentive a bit more until the total sum of the bids exceed the grid request.

5. Conclusion

This paper presents the development of table-top system of the MAS-based microgrid control system. The developed system consists of MGCC and multiple agents for distributed control of microgrids. This paper elaborates the details of the hardware development of the agents and also the software of the MGCC. Emergency demand response example has been tested on the overall HILS system. The agents are programmed to flexibly talk to the other agents and the MGCC via the CNP and then finally find a solution of each unit corresponding to a certain EDR request for peak shaving. More efficient intelligent algorithms for optimization and coordination will be developed for the multi-agents in the future work.

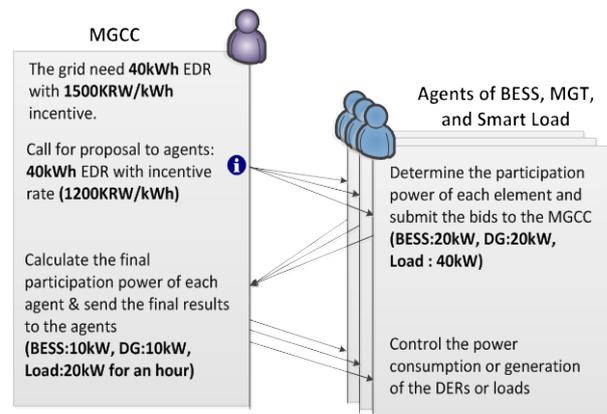


Figure 11. CNP procedure for dispatching EDR participation power.

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