An Agent-based Approach for Decentralized Control in a Heating Grid

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***Abstract*—The objective of this paper is to study the design and implementation of an agent-based model that provides decentralized control of a heating grid – a heating grid consisting of basic CHP plants, boilers, storages and residential loads. An agent-based application development involves model design, agent specification, application design, application implementation and scenarios discussion. This application uses JADE to develop the agents and MATLAB/SIMULINK to provide a simulated environment. The simulation results indicate that the proposed agent-based application can operate each heat generator to meet the future heat consumptions by using a priority-based decentralized control.**

Keywords—agent-based model, heating grid, decentralized control, JADE platform

I. Introduction

A. Motivation

As district heating is a significant portion in the German energy network, the control aspect towards the operation of heat units is of high importance. Given this fact, an agent-based approach is well suited for providing energy control and management systems in heating grids.

Heating grid systems are by their nature physically distributed. Conventionally, it is possible to collect all sensor data at each heat generator or heat storage, do all computations necessary for the control of a system at a single central computer. But there is a problem that the computation about future operations should be performed locally. The reason is that these computations need substantial amounts of sensor data, which otherwise needs to be communicated to a central computer. By making the prediction of heat unit operations locally, communications are decreased. Thus, it is a much more reasonable approach to develop local agent adopted for each type of heat unit.. In order to achieve this and to improve the robustness and flexibility of the whole heating grid, a decentralized control needs to be introduced in the agent-based model.

B. State of Art

Agent-oriented software engineering is at an early stage of evolution. Since 1980s, software agents and multi-agent systems have grown into what is now one of the most active areas of research and development activity in computing generally. The most important reason for the current intensity of interest is that the concept of an agent as an autonomous system, is capable of interacting with other agents in order to satisfy its design objectives. [1]

Recently multi-agent system technology is taking greater role in energy systems. Zhang Jian et al in [2] discussed the framework of MAS and presented an agent control model which aims to maximize efficiency of MicroGrids. M.Pipattanasomporn et al in [3] demonstrated the design and implementation of the multi-agent system for use in an Intelligent Distributed Autonomous Systems (IDAPS) MicroGrid.

II. Overview of The Heating Grid

The heating grid usually consists of heat generation, heat storage, insulated pipes and energy consumers.

The heat is often obtained from boiler units, a geothermal source or power plant designed for combined heat and power (CHP) which has a high level of energy utilization efficiency. Heat storage allows to store heat energy. After generation, the heat is distributed to customers via a network of insulated pipes.

In this paper, a simple structure of a heating grid is shown in Fig. 1. Among the CHP is the simultaneous generation of electricity and useful heat from a single fuel at high efficiency.

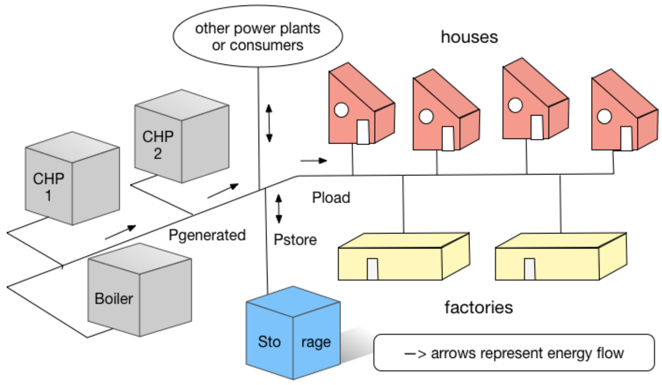

Fig. 1. Overview of a heating grid.

III. Architecture of the Agent-Based System

An agent-based model aims for simulating the actions and interactions of multiple agents in an attempt to re-create and predict the appearance of complex phenomena. [4] The idea behind an agent-based approach is to break down a centralized system into a decentralized system.

In this project, a hierarchical communication and control architecture has been developed. The proposed architecture consists of three layers to allow for robust and flexible data transmission and task assignment in a decentralized heating grid.

The architecture of an agent-based system is presented in Figure 2.

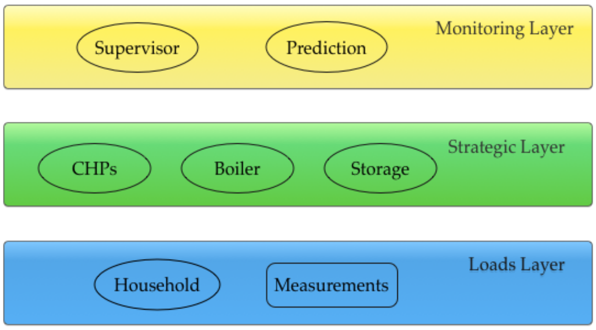

Fig. 2. Three-layer architecture of the agent-based system.

As seen from the Fig.2, the architecture consists of the three layers:

• Monitoring Layer: This layer consists of supervisor agent and prediction agent. It has an overview of the whole system.

• Strategic Layer: This layer consists of heat producer agents and heat storage agent that have strategic goals, making decisions based on control perspectives. Negotiations among the heat units can only take place at this layer.

• Loads Layer: The heat unit models receive consistent and informed control from the upper layer. The household agent can get the current heat consumption from the measurements and send notification to the monitoring layer.

IV. Design And Implementation

Many agent platforms are designed for developing an agent-based system. It is very important to select an agent platform that is based on a well-known standard -- IEEE standard [5] on Foundation for Intelligent Physical Agents (FIPA). This will help to ensure interoperability among different systems and platforms so that the proposed multi-agent system can be universally accepted. [6]

In this study, JADE (Java Agent DEvelopment Framework) is selected for application development. It simplifies the implementation of multi-agent systems through a middleware that complies with the FIPA specifications and through a set of graphical tools that support the debugging and deployment phases.

The agent-based system development involves model design, agent specification, decentralized control design and application implementation. Each step is explained below.

A. Heating Grid Model Design

Since this paper focuses on the design and implementation of an agent-based model, in this step, CHPs (Combined Heat and Power), boiler, storage and household unit are simply defined.

1) **The CHP model** has the input signal—*on/off.* Here, the output thermal power is only considered to be either 0 MW or maximum MW according to the most common operations of CHP.

2) **The Boiler model** has two input parameters: operation signal—*on/off* and *required power*. The operation of the boiler can be adjusted to meet the thermal power demand. Therefore, when the boiler runs, the output thermal power equals to the required power.

3) **The Storage model** has an attribute called *thermal capacity* which stands for the state of heat storage. A positive value means charging the storage and vice versa.

4) **The Household model** has the input – *received power* and output—*consumed power*. The consumed power is based on authentic or realistic sources. Consumption records for one year are used in this paper

B. Agent Specification

After the model design step, specifications of each agent are defined.

1) **The Household agent** is responsible for the interaction with the measurement. It monitors the actual heat consumption and sends the consumption data to the prediction agent.

2) **The Prediction agent** continually evaluates historical data and creates new predictions of future consumptions and sends these to heat unit agents.

3) **The Heat Unit agents** monitor the conditions of corresponding heat units. If one of these heat units has some accident, it will inform the supervisor agent. It is responsible for interactions with the other heat unit agents to decide the operation mode by a priority-based decentralized method. After the decision, it will pass the final decision to the Supervisor agent and the TCP agent.

4) **The Supervisor agent** is responsible for monitoring the whole grid, recording the operation mode and handling errors.

5) **The TCP agent** works as an interface to exchange data between agents developed in JADE and SIMULINK models at a regular interval. But in the real time application, it is not necessary, but only for the SIMULINK connections in this project.

The concepts of agents have been shown above, and then the interactions among different types of agents will be discussed.

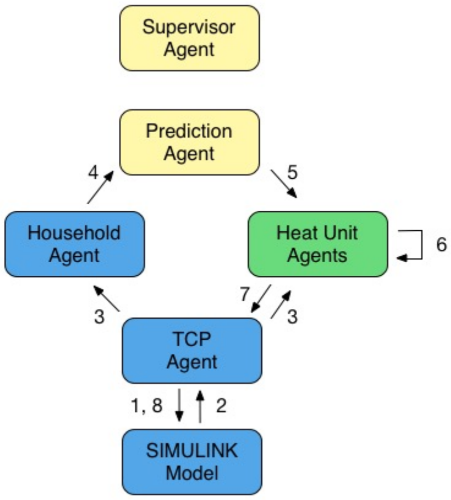

Fig. 3. Interactions of agents.

The Fig. 3 shows a loop of working interactions among different agents. The initialization of the agent-based system is performed by the Heat Unit agent, the Prediction agent, TCP agent and the Household agent. These agents notify the Supervisor agent of their presence. After the initialization process, the TCP agent passes the initial commands to the models in SIMULINK (1). Then, the models can run and deliver the necessary values separately to the Heat Unit agent and the Household agent (3) by means of the TCP agent (2). The Household Agent receives information about the current heat consumption and sends out this information to the Prediction agent (4). The prediction agent creates new predictions of future consumptions and broadcasts these to each Heat Unit agent (5). The Heat Unit agents coordinate with each other and decide the operation and the production amount (6). After negotiation, each Heat Unit agent will send its command to the SIMULINK models by means of the TCP agent (7). Finally, the models in SIMULINK receive the new command and run again with a certain sampling time (8).

C. Priority–based Decentralized Control

In order to show a complete and reasonable interaction among heat unit agents, four specified agents are defined: two CHP agents, one boiler agent and one storage agent. To realize the decentralized coordination among them, setting priority is an expressive way.

The order of the priority is assigned considering both financial and environmental aspects.

CHP units can use different types of primary energy e.g. bio methane, which is better for climate protection instead of natural gas. In addition, the switch times of CHPs should be reduced due to the expensive cost (e.g. maintenance). Therefore, those combined heat and power units own the highest priority.

Since the heat storage doesn't produce any thermal energy, and just allows excess thermal energy to be collected for later use, it can save much more costs compared to the operation of a boiler without storage.

Defined above, the priority of each energy production agent is shown in Table 1. The highest priority agent has the right to decide its own operation storage

TABLE I. PRIORITY ASSIGNMENT

Name	Priority
CHP1	1
CHP2	2
Storage	3
Boiler	4

Control and management strategies are critical for a heating grid. In this control strategy, a storage charging/discharging control algorithm is used. The main signal for the charging/discharging control algorithm is State of Charge (SOC). In order to protect the storage from a deep discharging and overcharging, the storage SOC will be regulated within a reasonable range (min% - max%). Note that this range can be easily changed based on design criteria and will not change the algorithmic framework. The following actions are taken based on detected conditions:

- Charging the storage if
    - min% < SOC < max% and Produced Power > Demand Power
    - SOC < min% and Produced Power >Demand Power
- Discharging the storage if
    - min% <SOC < max% and Produced Power < Demand Power
    - SOC > max% and Produced Power < Demand Power
- Import Power Generator if there is another available source
    - SOC < min% and Produced Power < Demand Power
- Export Power if there is another available load
    - SOC > max% and Produced Power > Demand Power

D. Application Implementation

The application implementation stage consists of several steps required to execute behaviors based on former steps. The application realization steps involve model establishment, agent creation, interface development and agent code generations.

The model establishment includes the CHP-, Boiler-, Storage- and Household implementations according to the former design.

The simplified heating grid model is shown in Fig.4. The CHP 1, CHP 2, Boiler and Storage provide heat to the households.

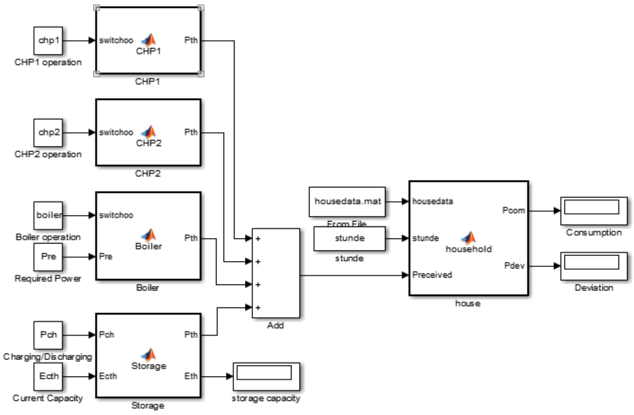

Fig. 4. A simplified heating grid model in SIMULINK.

And the attribute (maximum produced power) of each heat unit is shown in Table II.

TABLE II. THE ATTRIBUTES OF DIFFERENT HEAT UNITS ACCORDING TO AN EXAMPLE HEATING GRID

Name	max Energy/Power
CHP1	2.155 MW
CHP2	2.155 MW
Storage	10.10 MWh
Boiler	18 MW

The agent creation process involves the creation of each type agent. This is done by assigning certain tasks, rules and coordination regulations to each agent. In JADE, the actual jobs, or jobs, an agent has to do is carried out within "behaviours". It represents a task that an agent can carry out. The behaviours of each agent mainly include registry, sending/receiving messages, making decisions and handling errors. There are many kinds of behaviours such as *OneShotBehaviour*, *CyclicBehaviour*, *ThreadedBehaviour* and so on, which can be used according to the need of tasks.

The interface development step uses TCP/IP connections for SIMULINK and JADE to exchange data. The TCP agent opens a socket in JADE to listen the data from models in SIMULINK. Finally the agent code is generated which completes the application implementation.

V. SIMULATION RESULTS AND DISCUSSION

The simulation focuses on the control and energy management in the heating grid. In this section, the communications in JADE will be shown. Additionally, two scenarios are tested in the agent-based system.

A. System Analysis

To show the communications among the agents, JADE platform provides a sniffer agent which can monitor all message exchanges between a set of specified agents.

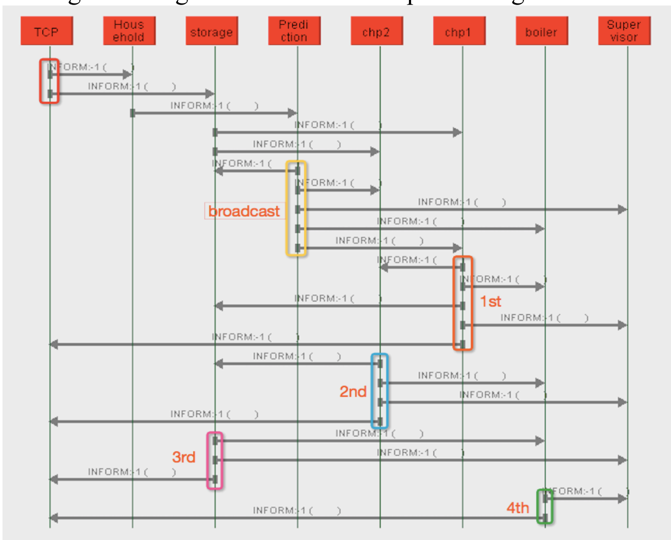

Fig. 5. The sniffer agent GUI.

The sniffer agent generates a sequence diagram. The Fig.5 presents the detailed communications based on the interactions of agents in Fig.3

B. Scenarios Discussion

The range of SOC is set between 30% and 70% in this paper for testing two simulated scenarios.

- Scenario 1: The first scenario is shown in Figs. 6 and 7: CHP1, CHP2 and the storage are enough to maintain SOC within an operation range, between 30%-70%, in order to avoid overcharging and deep-discharging.

- Scenario 2: The second scenario is shown in Figs. 8, 9 and 10: To avoid SOC from crossing the minimum limit of 30%, the boiler is imported and the storage won't be charged or discharged. In one day, the operation time of CHP is higher than 3, the CHP cannot operate any more in order to protect the CHP.

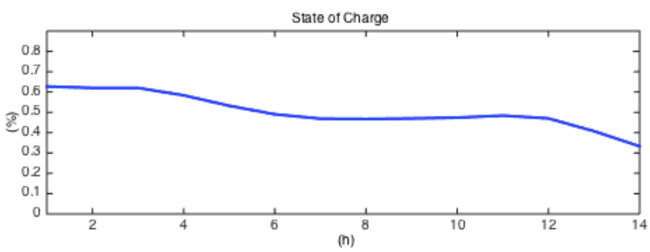

Fig. 6. State of charge for the first scenario.

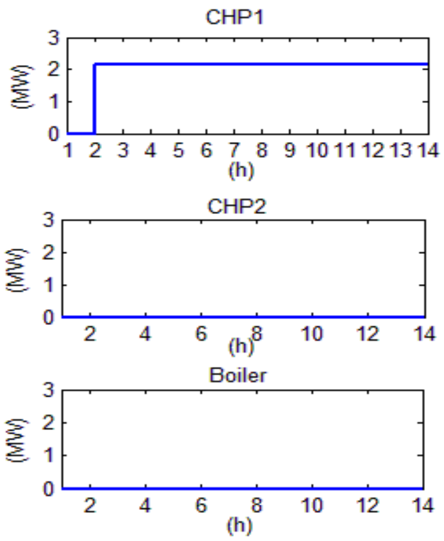

Fig. 7. Comparison of CHP1, CHP2, Boiler productions for the first scenario.

The simulation result of the first scenario shows the Storage capacity, the operations of CHP1, CHP2 and the Boiler in the system. Displayed in Fig.6, the state of charge is always kept between 30% and 70%. During this period, the sum of provided power including CHP1 and Storage can meet the demand power, so CHP2 and Boiler won't be used.

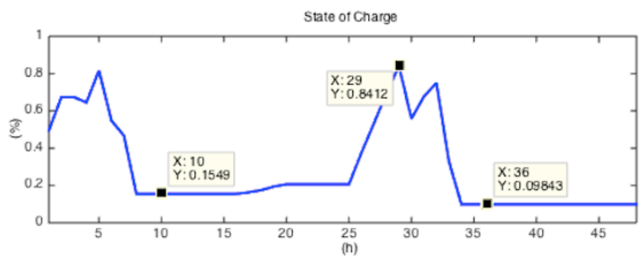

Fig. 8. State of charge for the second scenario.

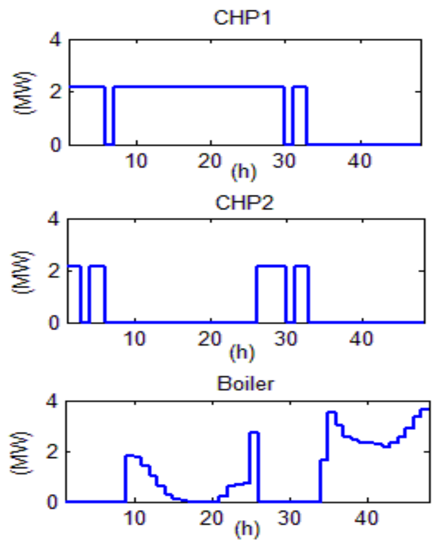

Fig. 9. Comparison of CHP1, CHP2, Boiler productions for the second scenario.

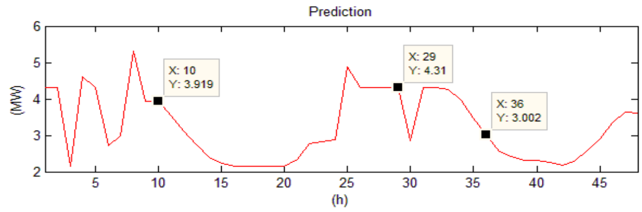

Fig. 10. Prediction power for the second scenario.

In the second scenario, the above figures show that the operations of different heat units will meet the future consumptions.

Before t=10, CHP2 switches on/off for three times. Since the switch times should be smaller or equal to 3, the CHP2 won't work anymore in this day.

At t=10, the state of charge is only 15.49%, which means it is much smaller than the minimum of the storage capacity. CHP1 switches on, but the heat amount of the CHP1 production is far less than the demand. Therefore, another heat generator source – boiler is imported to supplement the required energy.

At t=29, the state of charge reached a high level – 84.12%. The storage can meet the required power with the sampling time. So neither CHP units nor the Boiler will generate any heat at this time.

At t=36, the storage capacity decreased to 9.843%, but at the same time, the CHP1 and CHP2 switch times exceed 3 times. In order to generate heat, the boiler should work during the day.

VI. Conclusion and Future Scope

A. Conclusion

This paper presents an agent-based approach for decentralized control in a heating grid. The proposed agent-based system consists of a Supervisor agent, a Prediction agent, three Heat Unit agents, a Household agent and a TCP agent, developed in JADE. Agents exchange their messages via a TCP/IP protocol based on IEEE FIPA standard to ensure the system interoperability.

The given scenarios indicate that the agent-based system can control the heating grid to protect the storage from overcharging or deep discharging. In addition, it also can use pre-defined rules to restrict the operations of CHP units. This illustrates the capability of an agent-based system as a technology for managing the heating grid operation.

B. Future Scope

This project can be extended to a larger heating grid. Since this paper doesn't focus too much on the prediction algorithm, the forecast method can be improved to be more accurate. Heat exchange (selling/buying) functions for Household agent and markets can be implemented. Agent-based systems might be the most beneficial technology when different functionalities are integrated to create a system that is capable of controlling dynamic environments.

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