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A Market-based MAS Framework for Microgrids

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Abstract: This paper proposes a distributed multi-agent system (MAS) framework for market-based control in Microgrids. The proposed system consists of two main entities, Energy Selling Agents (ESAs) and Energy Buying Agents (EBAs). In order to alleviate the internal complexity of the agent, three kinds of delegate mobile agents are designed. They are issued by the corresponding agents according to their different functions assumed in the BDI (belief, desire, intention) architecture, such as one kind of delegate mobile agent fulfills the function for building and maintaining the environment information. Through the coordination and interaction of the agents and the delegate mobile agents, the energy exchange between the power resource units and the local loads is realized dynamically.

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1. INTRODUCTION

The use of small-scale generation connected to the local distribution systems, commonly referred to as 'Distribution Generation' (DG), has greatly increased during the last decades. Using DG to reduce the physical and electrical distance between generation and loads can contribute to improving reactive support and enhancing the voltage profile, removing distribution and transmission bottlenecks, reducing losses, enhancing the possibility of using waste heat and postponing investments in new transmission and large scale generation systems [Ackermann,T., et al., 2001; Pepermans, G., et al., 2005]. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "Microgrid" [Van, T. Vu., Belmans, R., 2006]. This approach allows for local control of distributed generation thereby reducing or eliminating the need for central dispatch.

An important aspect of Microgrids is to find a suitable control strategy that will take advantage of the inherent scalability and robustness benefits of distributed energy [Robert, H., Lasseter,R.2007]. Now, more and more distributed energy resources (DERs) and loads become intelligent electronic devices (IEDs) that are interconnected over information infrastructure, as indicated in Figure 1. Thus, distributed control can be applied on these IEDs with decision-making done locally. A scalable and robust energy system with each power resource and load can potentially be created. In this context, the agent technology is a suitable approach for autonomous control of distributed energy resource Microgrids.

In reference [Dimeas, A.L., Hatziagyriou, N.D., 2005], a central controller agent is proposed to optimize the Microgrids by coordinating the local controller of power producing unit and the local control of the consuming unit. Reference [Kok, K., Warmer, C., et al., 2005] also employs a similar central control agent (Power Matcher) to accomplish the system goal. In such kind systems, central control stations form single points of failure and may have scalability problems. Thanks to by having power resources, intelligent loads and storage devices following a common communication structure, adding (removing) power resources to meet the increasing (decreasing) load demand would be easier than the traditional way of incorporating new resources into a centralized control strategy. In such situation, other authors in [Vanthournout, K., Brabandere, K. D., et al., 2005] propose autonomous electricity networks (AEN). In such network, a group of distributed generators, intelligent loads and storage devices is capable of cooperation and control in a distributed manner, without central controller. The accomplishment of all this is based on standard components and public communication networks.

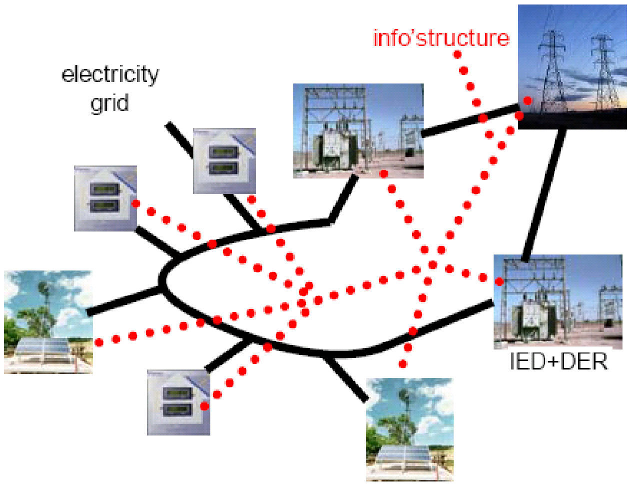

Fig. 1 Microgrids, consisting of DERs interconnected via the electricity grid (thick lines) and corresponding IEDs interconnected via the info'structure(dashed lines)

Based on electrical architecture and dedicated P2P network for the control proposed in [Vanthournout, K., Brabandere, K. D., et al., 2005], an additional layer on top of that is developed in this paper. A novel agent-based control framework for automatic control of a set of small power producing units and consuming units in a microgrid is described. The main task is to outline an agent-based architecture and to define the functions of the agents according to the characteristics of the energy resources and load. In this distributed microgrid control system, every energy resource which produces the electricity energy is managed by an Energy Selling Agent (ESA), while each load as a power consuming unit is controlled by an Energy Buying Agent (EBA). The ESAs offer EBAs the commodity-electrical energy at a certain price and amount. The goal pursued by the EBAs is to buy the electricity energy not only to meet its demand amount but also at the lowest cost.

In the proposed framework, the MAS architecture follows the BDI (belief-desire-intention) architecture. BDI-based agent architectures have proven their usefulness in building MASs for complex systems especially thanks to their explicit ability to cope with dynamic environments [Rao,A.S., Georgeff, M.P.1995]. The three states of a rational agent represent, respectively, the information, motivational, and deliberative states of the agent. These mental attitudes determine the system's behaviour and are critical for achieving adequate or optimal performance when deliberation is subject to resource bounds. It is novel that these three different functions (belief-desire-intention) of BDI are fulfiled by three kinds of the delegate mobile agents issued by the ESAs and EBAs respectively. The delegate mobile agents are issued either by ESAs for building and maintaining information on the environment or by EBAs in order to explore options on behalf of agents and to coordinate their intentions. The introduction of the delegate mobile agents allows agents to dynamically deploy its components to arbitrary network sites and re-deploy those components in response to a changing environment. Due to the clear function division of agents and delegate mobile agents, the software architecture becomes more structural and transparent. Through the coordination of two kinds of agents and three kinds of delegate mobile agents, the energy exchange between energy resource units and load units is realized. A distributed power matching architecture in microgrid is set up. Such agent-based control framework has the advantage of scalability, flexibility and reliability, which is suited for control of microgrid.

This paper is structured as follows. Section 2 outlines the agent-based control framework. The behaviour and function of each agent and delegate mobile agent is also illuminated in details in this section. Sect. 3 describes the software simulation. Section 4 ends with conclusion.

2. AGENT-BASED CONTROL FRAMEWORK

In the proposed agent framework, each energy resource unit and load unit in the microgrid is represented as an autonomous agent that provides a communication interface which is common to all different components in the system. In details, an energy resource unit is managed by an energy selling agent (ESA); a load is controlled by an energy buying agent (EBA).

In a microgrid system, an ESA is an abstraction of the production means such as diesel generator, wind generator or battery and so on, while an EBA represents the electrical utility such as communication device, industrial and domestic facility.

The control strategy for the represented energy resource or load is completely incorporated in the software part of the agent. With each agent running on a separate computer, the energy system is distributed.

The agent-based distributed energy resources microgrid researched in this paper is shown in Fig.2. In this figure, the slim solid lines (laid in bottom) represent the power grid. The common communication network is represented by the thick line (laid in the upper) shown in the figure, which interconnects each agent in the system. In this figure, only the microgrid is studied, not mention the interaction with the rest of the outside electricity grid.

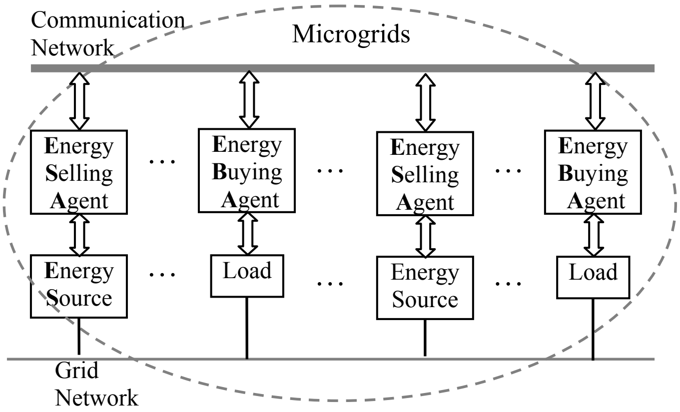

Fig.2. Agent-based control framework for DER microgrids

This agent-based framework facilitates self-organization. In such system, each agent is independent. When a new agent joins the system, it is easy for the new one to interface to the existing agents. A common method for the interface is through a directory service whereby agents register themselves to a common directory and then self-organize their activities. The ability for agents to be self-organized contributes to the scalability and robustness of the Microgrids. Since the system is self-organizing, there is no limit to how many agents can join the Microgrids at one time and no restrictions on when an agent should/can join. If an agent goes offline, the other agents are able to cope with the loss of that one agent and reorganize the system.

The main agents and their functions are described as follows.

2.1 *Energy Selling Agent and Energy Buying Agent*

A. Energy selling agent (ESA)

An energy resource can be viewed as a generic resource. It is managed by a corresponding Energy Selling Agent. So the ESA is like a resource manager whose work is based on the local measured information and the communication with other agents. The resource manager handles how much energy will be supplied and directs the corresponding energy resource to do so. It also determines all requests for access to that resource. Control strategies for different types of energy resources may be different from each other, depending upon the characteristics of the fuels.

As a resource, the ESA offers the energy consuming unit functionality to satisfying a certain demand of electricity at an amount and price. The ESA needs to schedule its energy resource usage based on requests from the loads and can re-schedule resources when a higher priority load sends a new request. The communication between the load and ESA solves “what-if questions”. These include the following questions from the load.

- Whether the electrical energy is available for an EBA to book the energy resource at next time slot.
- If available, how much electrical energy can be supplied by this energy resource unit?
- If available, what’s the price for the requested amount of electrical energy?
- Whether the former contract is cancelled? Because if ESA receive a contract request from an EBA with higher priority, the ESA should cancel the previous contract from the lower priority EBA. In such situation, when the lower priority EBA asks whether the contract is available, ESA should notify the availability status of the contract. The process will be depicted in details in later section.
- If getting the answer for all these questions, EBA can evaluate the satisfaction degree of its own demand.

B. Energy Buying Agent (EBA)

Each load as power consuming unit (PCU) is controlled by a corresponding Energy Buying Agent (EBA). An EBA is responsible for guiding its entity (load) through the environment to explore the available energy resources and find the most optimal one. In order to fulfil the task, the decision-making process of the EBA takes the following steps: observing the environment, considering possible options, deciding a final option and communicating this with the ESA. The EBA should have the ability to renew its intention (i.e. buy energy from the specific energy resource unit) when the situation in the environment changes.

This kind of agent needs to explore the feasible energy supplier or supplier combinations according to its demand in microgrid environment. This feasible supplier or supplier combinations correspond to a task scheme. This scheme includes the energy amount and energy price. An EBA needs to consider all possible schemes (i.e. various combinations of suppliers) which can bring the current task toward its goal in an optimal way, and match these desires with the feasibility information. The combinations of energy resource units that match a suitable scheme represent the different options that the EBA chooses to achieve its goal. Exploring a combination means to evaluate the method in a “what-if mode” in order to judge the price and amount if this combination would be chosen by the EBA. For example, if an ESA cancels the contract which is made previously with an EBA, this EBA should re-compute the solution set and re-choose a new intention.

C. Conflict resolution

It can happen that more than one load wants to choose the same energy resource or resource combination for its cheap price or other reasons. In this situation, a conflict happens, which is solved by some rules used as ESA’s intelligence:

- The different kinds of loads have a different priority for booking the resources, according to their characteristic. For example a communication device has a higher priority than a washing machine.
- When having the same priority, the buyer with larger demand amount has a higher priority than the smaller one. From the view point of the energy resource unit’s profit, it makes sense that the more power to sell, the more profit the seller can get.

2.2 Delegate mobile agents

From the description above, we can see that the task of two agents (ESA & EBA) is rather heavy. Consequentially, the internal structure of the agents is complex when implementing them into software. In order to alleviate this internal complexity, three kinds of delegate mobile agents are designed. A mobile agent is an executing program that can migrate during execution from machine to machine in a heterogeneous network. On each machine, the agent interacts with stationary service agents and other resources to accomplish its task [Brewington, B., Gray, R., et al.,1998]. The delegate mobile agents in this system can travel in the computer network and fulfil the different functions appointed by their generator. Consequently, through this delegate mode, the three aspects of BDI are realized.

- Feasibility Mobile Agents (FeasibilityMAs) are issued by the ESAs and deal with the observations of environment. They achieve the B (beliefs) of B-D-I.
- Exploration Mobile Agents (ExplorationMAs) are issued by the EBAs and consider all possible options to achieve the system goal. This kind of delegate agent performs the D (desires) of B-D-I.
- Intention Mobile Agents (IntentionMAs) are issued by the EBAs to choose an optimal option. The I (intention) of B-D-I is achieved by this agent.

A. Feasibility Mobile Agent (FeasibilityMA)

The ESAs generate FeasibilityMAs which explore the feasible energy resources in the environment. The function of the FeasibilityMAs is to realize the agents’ perception about the environment. The behaviour of a FeasibilityMA is as follows.

In the communication network, every node represents an energy resource unit or a load. Each ESA sends one FeasibilityMA to each neighbour node connected to it. The FeasibilityMA moves to the nodes and firstly judges whether this node is an energy resource unit. If not, this FeasibilityMA does nothing and turns back to the ESA. Otherwise, this FeasibilityMA will carry out the querying interactions with the ESA managing that energy resource unit. The interaction is to query some information such as the energy amount this node can provide and the price. The generator ESA stores all information carried back by all FeasibilityMAs into local information spaces. Thus, the ESA sets up a table which contains all the neighbour ESA's information including IP address, energy amount and energy price. Thus, the FeasibilityMAs precept the whole world through the partial environment. This point reflects a significant feature of the agent: having partial or none at all representation of the environment. The goal of MAS is to control a complicated system with minimum data exchange and computational demands [Wooldridge, M., 1997]. This distributed algorithm obtains the global information on a distributed network for local nodes, without central coordination. In order to accommodate the dynamic changes in the environment both on the network topology and information of the energy resource unit, the ESA will refresh FeasibilityMAs at a certain frequency.

B. Exploration Mobile Agent (ExplorationMA)

The EBAs generate ExplorationMAs to explore the feasible energy resource units like scouts and make evaluation. Using the feasibility information available locally, an EBA is able to find out which ESA or ESAs are physically or virtually feasible for achieving its goal. The explore process goes as follows:

ExplorationMAs are sent to ESA nodes randomly by an EBA. These ExplorationMAs interact with the local ESA by asking how much energy can be bought and how much is the cost of per energy unit. If the demand energy amount is satisfied, the ExplorationMA turns back to the EBA with these information. Otherwise, ExplorationMA will select the next node to visit from the ESA's local information table. The ExplorationMAs repeat this process until the demanded energy amount is satisfied. Afterwards, the ExplorationMAs return and report back to their base EBA with the information including the combination of ESA, the IP address of ESA, the available energy amount respectively provided by each ESA and the total price if buying energy from these ESAs. Thus, ExplorationMAs make this evaluation through visiting all the ESAs one by one. Like the FeasibilityMAs, the ExplorationMAs are refreshed regularly to percept the invalid or infeasible candidate due to the environment changes. In fact, the function of ExplorationMAs is to provide the available solution sets to the EBA's task.

C. Intention Mobile Agent (IntentionMA)

After all the ExplorationMAs return back, an EBA receives a set of valid energy resource combinations to choose. After the evaluation according to the certain criterion, the EBA selects one combination to become its intention. IntentionMAs generated by EBAs propagate the intention of EBAs through the environment. In this market-based architecture, the criteria used for the selection by EBAs are the smallest cost when buying energy from these ESA combinations.

The IntentionMAs follow the selected combination, and virtually execute the energy bargain process of their selected candidate solution. On their virtual journey, the IntentionMAs acquire the price and amount each energy supplier can provide. Any changes, which occurred after the exploration, immediately become visible when these ESAs provide the information. In contrast to the ExplorationMAs, IntentionMAs inform the ESAs that a particular electricity user wants to buy the energy from them at certain time slot. In this way, IntentionMAs make a contract on the energy, and the ESA adjusts its power distribution to account for this visit. As a consequence, ESAs are able to allocate their electricity energy more accurately to their visiting Exploration and Intention mobile agents. Similar as ExplorationMAs, IntentionMAs report back to their base EBAs to inform about the schedule of the contracts.

The agents and delegate mobile agents and their relationship depicted above can be schematically illustrated by Fig.3.

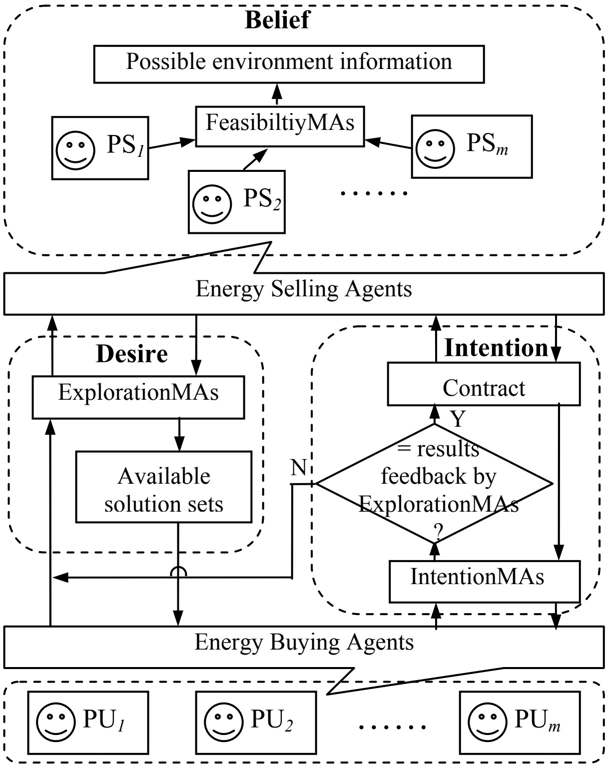

Fig.3. The Agents, delegate Mobile agents and their coordination

2.3 Coordination

To achieve the goal of the system, coordination is very important. In this BDI system, it can be observed that coordination occurs between

- the Energy Selling Agents and Energy Buying Agents

- three types of mobile agents and Energy Selling Agents
- three types of mobile agents and Energy Buying Agents

3. SOFTWARE SIMULATION

To demonstrate the effectiveness of the proposed agent based control framework, simulation studies have been performed using JAVA programming language and the Eclipse tools. The goal of demo program is to emulate a microgrid environment. In the program, the microgrid is depicted by a network graph. The energy resource units and loads are connected not only by the power line but also by the communication network. The energy resource units and loads can be added or deleted to emulate the entrance to or quit from the Microgrids without influencing the operation of the existing entities in the Microgrids. The main parts in the program are depicted in details as follows.

EnergySellingAgent: is the class for the energy resource agents. It represents the available power resources. It changes with the time and shows different power quantity according to the inquirers' priority. It's a rather dynamic agent. It has certain key attributes, such as volume (power amount), free-volume (the available power quantity), name, price, IP address and so on. It also records all the contracts that have been made with the *IntentionMAs* delegated by *EnergBuyingAgent*. Some contracts have been made will be revoked due to the conflicts in the multi-agent environments. So, it provides methods to cancel the contracts as well as make the contracts.

EnergBuyingAgent: represents the energy consuming units-load. It has the normal attributes such as name, volume, priority and IP address. In its implementation, the delegate pattern is used which greatly reduces the complexity in implementing the *EnergBuyingAgent*. Most work is done by the *ExplorationMAs* and *IntentionMAs*. In addition to the methods that manipulate the two main types of mobile agents, it also records all contracts that have been signed. It also provides methods to cancel these contracts.

FeasiblityMAs: This class is an abstract class. It represents the agent's knowledge mining process. In the basic assumption of our system, the energy resource units and energy consuming units could not get system global information. But the energy resource units can get certain knowledge around its environment by *FeasiblityMAs*. This process is delegated to the *FeasiblityMAs*. *FeasiblityMAs* reach to its neighbour node travel around the environment and get the information of the energy resource units such IP address, price and energy amount. It keeps the list of possible available power suppliers.

ExplorationMAs: Based on the information returned from the *FeasiblityMAs*, the *ExplorationMAs* are sent out by *EnergBuyingAgent*. It will interact with the *EnergySellingAgent* to get current real available volumes and compute the best combination to use the current available information. Different *ExplorationMAs* will return the different solutions according to its knowledge getting from the enviornment. Implementation of this class involves a lot of vector programming and ordering programming. The java Comparable interface is used to achieve this job.

IntentionMAs: After the *EnergBuyingAgent* compares the results feedback by the *ExplorationMAs* and does the decision, the *IntentionMAs* are generated. It will visit the *EnergySellingAgent* chosen by the *EnergBuyingAgent* to virtually make trade. This class provides the method to compute the final cost. Another important method provided by this class is to *makecontract*. This method yields a list which contains the particular *EnergySellingAgent*. All these agents have successful contract with the *EnergBuyingAgent* which is the base generator of the *IntentionMAs*.

SimulationEngine: It is very important for the system operation. In the program, the method fulfilling this function is public void beginsearchProcess(). First, all *EnergSellingAgents* send out the *FeasiblityMAs* to collect the environment information. Second, *EnergBuyingAgent* send out the *ExplorationMAs* to carry out searching unit the certain requirement is satisfied. In the program, the variable *isAlldetermined* is an important indicator, which indicates the status of contract made between the *EnergSellingAgents* and *EnergBuyingAgent*. Through judging the value changing of this indicator, *ExplorationMAs* will be refreshed by the corresponding *EnergBuyingAgent*. That means the agents adapt the environment changing and re-plan its desires and intention.

The simulation results show the approach proposed has a number of desirable general features:

• Scalability. From the view point of the system architecture, it can be handled that the situation where the number of units (the energy resource units and loads) in the system becomes large. All the agents are autonomous. The system global goal is achieved by these distributed autonomous entities.

• Flexibility. The overall goal of loads and energy resource units matching is achieved by coordination between many small programs (in the simulation program, it refers to the object and class) with local information and intelligence, rather than by a single point of control that has to "know and steer everything." This gives a much more flexible and natural architecture in this highly distributed applications.

• Adaptability. The proposed approach deals well with the common situation whereby the environment of the system is changing dynamically with loads and energy resource units entering or disappearing at unknown and irregular times.

In this case study, the detailed communication issues such as delay is ignored since the objective here is to verify the feasibility of the agent-based control framework for DER Microgrids. A hardware platform is under construction. It consists of several power electronic converters, which are electrically interconnected via a microgrid and whose IEDs are logically interconnected via off-the-shelf communication protocols (TCP/IP). Each converter can be used to emulate generators or loads in a dispersed electricity generation environment. This platform allows different control algoritms to be modelled in a high level programming tool such as

JAVA. As these converters are connected to PCs, they can be interconnected via TCP/IP modules.

4. CONCLUSION

This paper applies the BDI MAS architecture to power systems for controlling energy resource units and energy consuming units matching, with agents and delegate mobile agents.

In the system proposed, the virtual entities in this environment are energy resource units and energy consuming units. They are controlled by the ESAss and the EBAs respectively. It is assumed that in such environment the agents are separate from each other and have partial or none at all representation of the environment. The mechanism of FeasibilityMAs provides a good way by which MAS can perceive the world only using the limited information. This point reflects the core of the agent technology.

Introduction of the delegate mobile agents alleviates the internal complexity of an agent. The FeasibilityMAs, ExplorationMAs and IntentionMAs realize the beliefs, desires and intentions of BDI architecture. The collaboration and interactive between the agents and the delegate mobile agents achieve the goal of the application. These collaborations repeat until all the agents achieve their goal. Through refresh of delegate mobile agents, the agents can discover the change of environment and renew the intention. For instance, when the EBAs detect the change of the contract availability status through the refresh of intention mobile agents, the new decision will be made according to the information feedback by the FeasibilityMAs and ExplorationMAs.

This paper sets up a totally distributed control system. It makes sense to control the energy resource units and energy consuming units using the proper agent system framework from the viewpoint of themselves (i.e. self-organize). Traditionally, a multi-agent system in microgrid had a central operating agent which gathers all system knowledge and makes the decision. This central coordinator plays important role in the whole system and will provoke considerations about scalability, computational complexity and communication overhead. But the MAS architecture proposed in this paper can reduce these concerns. All agents and delegate mobile agents only serve to the specific physical entity in the environment. Even if one or more units are broken down, the performance of the whole system will not be damaged. The broken units quit the system automatically and re-enter the system after they are repaired. In short, the adaptability of system is increased.

The emphasis of this paper is laid on the MAS framework of the energy resource units and energy consuming units matching, not considering the dynamic pricing mechanism to handle the energy resource optimally. The further work will be done on merging auction algorithms to the agent activity. The dynamic pricing mechanic not only can solve collision effectively but also can increase the simultaneous interest between the production and consumption of electricity.

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