Multi-Agent Coordination for DER in MicroGrid

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Abstract—**Multi-agent system (MAS) is one of the most exciting and the fastest growing domains in agent oriented technology which deals with modeling of autonomous decision making entities. This paper presents an application of MAS for distributed energy resource (DER) management in a MicroGrid. MicroGrid can be defined as low voltage distributed power networks comprising various distributed generators (DG), storage and controllable loads, which can be operated as interconnected or as islands from the main power grid. By representing each element in MicroGrid as an autonomous intelligent agent, multi agent modeling of a MicroGrid is designed and implemented. JADE framework is proposed for the modeling and reliability of the MicroGrid is confirmed with PowerWorld Simulator. Further, the FIPA contract net coordination between the agents is demonstrated through software simulation. As a result, this paper provides a MicroGrid modeling which has the necessary communication and coordination structure to create a scalable system. The optimized MicroGrid management and operations can be developed on it in future.**

I. Introduction

MUlti Agent technology is one of the most exciting fields in the intelligent resource management**.** Recent developments [1, 2] have produced very encouraging results in its novel approach to handle multi-player interactive systems. In particular, the multi-agent system approach is adapted to model, control, manage or test the operations and management of MicroGrid. Agents represent individual entities in the network. Each participant is modeled as an autonomous participant with independent strategies and responses to outcomes. They are able to operate autonomously and interact pro-actively with their environment. Such characteristics of agents are best employed in situation like MicroGrid modeling.

The deregulated energy environment [3, 4] has favored a gradual transition from centralized power generation to distributed generation (DG) where sources are connected at the distribution network. These DG sources comprise several technologies, like diesel engines, micro turbines, fuel cells, wind turbines and photovoltaic. The capacity of the DG sources varies from few kWs to few MWs. Distributed systems can also bring electricity to remote communities not connected to a main grid. Such multiple communities can create a MicroGrid of power generation and distribution.

The common communication structure and distributed control of DG sources together with controllable loads and storage devices, such as flywheels, energy capacitors and batteries, is central to the concept of MicroGrids [1]. MicroGrid can operate as interconnected to the main distribution grid, or as islanded if disconnected from the main distributed grid. From the grid's point of view, a MicroGrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load and as a small source of power or ancillary services supporting the network. From the customers' point of view, MicroGrids similar to traditional LV distribution networks provide thermal and electricity needs. In addition, MicroGrids enhance local reliability, reduce emissions, improve power quality by supporting voltage and potentially lower the cost of energy supply.

The literature shows varieties of applications of MAS in power system especially in MicroGrid. The optimization of interconnected MicroGrid operation [5] was done by optimizing production of the local DGs and power exchanges with the main distribution grid. In the application of MicroGrid control, Dimeas et al [6] research shows how the local intelligence and the social ability of the agents may provide solutions in the optimal and effective control. Authors in [7] invented the new concept for a distributed power system with agent technology as (Intelligent Distributed Autonomous Power Systems) IDAPS which is a specialized MicroGrid for coordinating customer owned DERs. In addition, MAS has been applied successfully in the other power system operations too. For instance, switching and restoration [8] in power system.

This paper provides multi agent modeling of a MicroGrid which can be extended easily to perform MicroGrid management and control operations. A simple PoolCo market simulation [9,10,11,12] illustrates the implementation of coordination between agents in the MicroGrid modeling.

II. Multi agent system approach

A. Multi Agent System

Multi agent technology has been successfully applied to power systems management and operations recently. Each power source and load in the system is represented as an autonomous agent that provides a common communication interface for all the other agents representing the other components in the network.

The basic element of MAS is the agent which can be described as a piece of software with some characteristics. Some of the important characteristics of agents in the MicroGrid are;

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1) Agents are capable of acting in the environment which means the agent is capable to change its environment by its actions. For instance, an agent that controls a storage unit and intends to store energy, rather than to inject it, alters the decision and the behavior of other agents.

2) Agents communicate with each other. This is a part of their capability of acting in the environment. For instance, agents controlling micro sources communicate with the market operator (MO) and the other agents in order to negotiate for the internal MicroGrid market.

3) Agents have a certain level of autonomy. This means that they can take decisions driven by a set of tendencies without a central controller or commander. The autonomy of each agent is related to its resources. For example, the available fuel, in case of a production unit.

4) Agents represent the environment partially or fully. Each agent not only knows the status of the unit but also informs via conversation with the other agents about the status of the neighboring agents or sub systems.

5) Agents have certain behaviors and tend to satisfy certain objectives using its resources, skills and services. For instance, one skill could be the ability to produce or store energy and a service could be to sell power in a market. The way that the agent uses its resources, skills and services defines its behaviors. As a consequence, the behaviors of each agent are formed by its goals. An agent that controls a battery system aiming to provide uninterruptible supply to a load has a different behavior than a similar battery system. As a whole, the behaviors of MAS are formed by the system goal which is to maximize benefits of system managerial operations.

B. *Advantages of MAS Approach*

Multi agent system approach has several advantages over the traditional approaches for management and control of MicroGrid. Some of the important advantages of the MAS approach are;

1) Unit autonomy: Depending on the goals of the unit owners, the various units in a MicroGrid can behave mostly autonomously in a cooperative or competitive environment. This is a basic characteristic of an agent.

2) Reduced need for large data manipulation: The agent based approach suggests that the information should be processed locally and the agents should exchange knowledge. In this way, the amount of information exchanged is limited and so is the demand for an expensive communication network. This feature is common to the traditional distributed computing. Moreover, the multi agent system is characterized by the fact that agents have partial or no representation of the environment. In our application the agent of a unit only knows the active power level of its own bus and based on which, it can estimate what is happening at other buses, but it has no information about the whole MicroGrid.

3) Increased reliability and robustness of the control system: In case one of the controllers fails, other agents may adapt and continue the system function.

4) Openness of the system: Multi agent system allows any manufacturer of DER units or loads to embed a programmable agent in the controller of his equipment according to some rules. In this way, the required “plug and play” capability for installing future DER units and loads can be provided.

Distributed coordination for DER, a potential method to realize these benefits, can be implemented by using multi agent technology.

III. MicroGrid Modeling

A. *Agent Platform*

Agent platform is a software environment where software agents run. JADE (Java Agent DEvelopment) framework [13] is an agent platform proposed for this project. JADE aimed at developing multi-agent systems and applications conforming to FIPA standards for intelligent agents.

JADE is a middleware which is a software platform that provides another layer of separation between the software and operating system. In this implementation, the underlying operating system is the Java Virtual Machine, the middleware is JADE and the application is the code for the agents written in Java.

JADE is also the runtime environment in which agents execute, and therefore hides from the agents the underlying complexity of the operating system or network. Agents can span multiple computers or be on one computer, yet for the implementation, the code for sending and receiving messages is the same. The JADE runtime manages the agent's life cycle, queuing and sending of messages, and interaction with the directory services. The JADE runtime in turn executes within a Java Virtual Machine.

Every agent is in a container and a collection of containers make up a platform. There can be multiple containers on a computer, but containers cannot span computers. A platform encompasses all the containers within an agent system and therefore can span multiple computers.

The simulation takes advantage of the administration services provided by the JADE runtime, primarily the directory service. The directory services and other administration services are hosted on the Main Container, which is the first container launched in the platform, but are duplicated on the other containers for robustness.

JADE platform provides a set of functions and classes to implement agent functionality, such as agent management service, directory facilitator and messaging passing services which all are specified by FIPA [14] standards. Agent management service (AMS) is responsible for managing the agent platform which maintains a directory of AIDs (Agent Identifiers) and agent states. AMS provides White page and life cycle services. Directory facilitator (DF) provides the default yellow page services in the platform which allows the agents to discover the other agents in the network based on the services they wish to offer or to obtain. Finally, the message transport service (MTS) is responsible for delivering messages between agents.

B. *Software System Analysis*

The ultimate goal of the project is to develop an agent-based solution for managing and controlling distributed energy sources in the MicroGrid. The scalability and robustness are the main key attractive features of this software development.

The system allows for scalability in terms of adding any number of agents to the system at any time. Through a common directory service, each agent registers their abilities. As the system grows, there could potentially be network congestion. Because of fast processors today and large bandwidth over networks, it seems that system size scaling should not be a problem. There are no limits within JADE of how many agents can be registered on the same platform.

The system robustness is another property to analysis. Each agent can be run on a separate computer so the failure of one computer will only remove one agent and the system can continue to function, with a performance loss of the physical capability of that failed device. By using the backup features of JADE, the directory service can be duplicated on every computer. Only one container with administrative services is active at a time; with the failure of that container, JADE is able to migrate essential administrative services to other computers to create a fully distributed system that is inherently robust. With the design based on contact net, at every contract net cycle new agents are included in the process and missing agents are no longer considered. However, if an agent is removed while currently fulfilling a contract, then that contract is left unfilled and there will be shortfall somewhere. Because the contracts are short in length, this does not affect the system dramatically.

The created simulation is fully distributed. The agents in an energy node configuration can be run on any number of machines without changing the functionality of the system. The same configuration can be used with all agents on a single machine and with agents running on separate machines. Because of the Java-based tools used, the system is platform independent and has been run with a mix of Windows-based and Linux-based agents.

C. *Distributed Control System*

It is very important that the integration of the micro sources into the LV grids, and their relationship with the MV network upstream which will contribute to optimize the general operation of the system [6, 19].

Distributed control of MicroGrid has three levels which are distribution network operator (DNO) and market operator (MO) at the level of the medium voltage, MicroGrid central controller (MGCC) and local controllers (LC), which could be either micro source controllers or load controllers.

The DNO is responsible for the technical operation in a medium and low voltage area, where the MicroGrid exists. The MO is responsible for the market operation of the area.

The main interface between the DNS/MO and the MicroGrid is the MicroGrid Central Controller (MGCC). The MGCC is the main responsible for the optimization of the MicroGrid operation, or alternatively, it simply coordinates the local controllers, which assume the main responsibility for this optimization. The lower level of control consists of the LC. The LCs control the Distributed Energy Resources, production and storage units, and some of the local loads. Depending on the mode of operation, they have certain level of intelligence, in order to take decisions locally. For example for voltage control, the LCs do not need the coordination of the MGCC and all necessary calculations are performed locally.

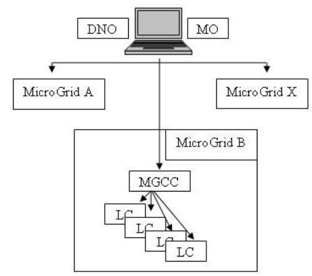

Fig. 1. MicroGrid Control Architecture.

There are several levels of decentralization that can be possibly applied, ranging from centralized control to a fully decentralized approach. According to the fully decentralized approach, the main responsibility is given to the DER controllers, which compete to maximize their production in order to satisfy the demand and probably provide the maximum possible export to the grid taking into account current market prices. Furthermore, LCs should take all the appropriate decisions to ensure safe and smooth operation of the DER which they are controlling.

IV. SIMULATION

A. *Proposed Scheme*

In order to demonstrate the multi-agent coordination for DER in a MicroGrid based on contract net approach [14], a simulation system needs to be created with specific agents to visualize each element interacting with others in a common environment. A specific implementation has been coded to demonstrate an instance of MicroGrid management operations which is PoolCo market operation. The main task of this market algorithm is to centrally dispatch and schedule DER in the MicroGrid. The operating mechanism of the PoolCo model is described below.

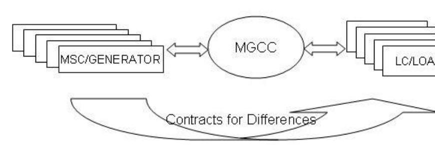

Fig. 2. PoolCo Model.

In the PoolCo market operation, generators and loads submit their bids to pool, in order to sell power to the pool or buy power from the pool. All the generators have right to sell power to pool but never specify customers. If generator agents' bids are too high, they have low possibility to sell power. On the other hand, loads compete for buying power. If load agents' bids are too low, they may not be getting any power at all. In such a model, low cost generators and high demanded loads would essentially be rewarded.

During PoolCo operation, each player will submit their bids to the pool which is handled by MGCC. The MGCC sums up these bids and matches the demand and supply. The

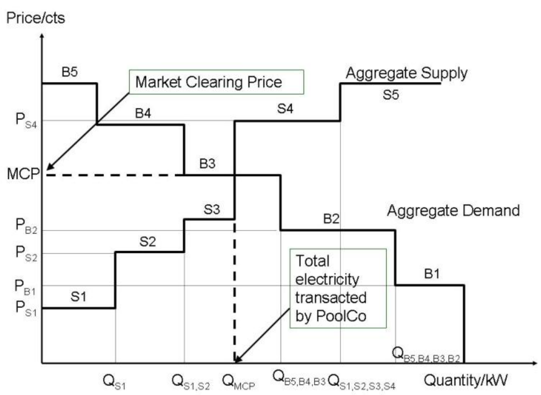

Fig. 3. PoolCo market clearing.

MGCC will implement the economic dispatch and produce a single spot price for electricity giving participants a very clear signal of the market forces. This is called the market clearing price (MCP). The MCP is the highest price in the selected bids in PoolCo. Winning generators are paid the MCP for their successful bids while successful bids of loads are obliged to purchase electricity at MCP.

The simulation will run through five sequences of stages, starting from agent world creation and initialization. Then

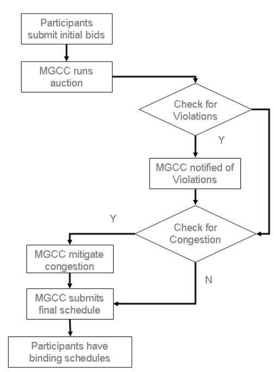

Fig. 4. General flow of simulation.

clearing of the market, scheduling the DER and checking congestion and reliability will follow. Finally, system will finalize and seal the contracts. The general flow of the programming is shown in Fig 4.

The multi agent system can be started up via the agent launch pad. System contents its administrative agents, and agents representing generators, loads, storage, local controllers and other power system elements. All the agents are created and launched as static agents in a local machine. Then they execute their own thread of initialization. The initialization of generators and loads consist of their generation capacities, load requirements and bidding price by obtaining from a database in the simulation environment. When all the parameters of the agent are properly initialized, each agent will autonomously register themselves with the DF as their first task.

As soon as the agents register themselves with the DF, the agents will query the DF for a complete listing of agents and their services on the network using a certain search constraint. These search constraints are usually queries to the DF for agents with a certain type of services or agents with certain types of names. Generators will send a query to the DF on all other Loads agents and MGCC. Loads will send a query to the DF on all other Generators agents and MGCC. The DF will reply these requests with listing of all agents that matches their search constraints and all the physical addresses of these agents.

B. Coordination between Agents

The coordination between agents is an important issue in the MAS modeling. In this paper, the agents coordinate among themselves in order to satisfy the energy demand of the system and accomplish the distributed control of the system. The coordination strategy defines the common communication framework for all interactions between agents. Simple contract net coordination [14] was chosen because it is one of the simplest coordination strategies. All discussions between agents are started simply by a requesting agent asking the other agents for a proposed contract to supply some commodity, and then awarding

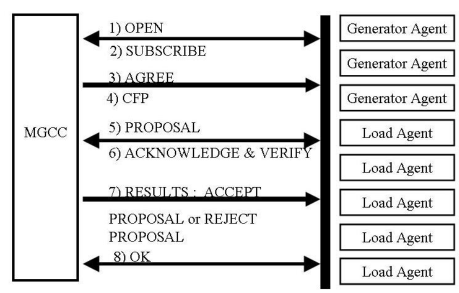

Fig. 5. Communication between Agents: Contract- Net protocol.

contracts from the returned proposals in a fashion that minimizes cost or fulfils some other goal. The disadvantage of simple contract net coordination is that only simple negotiation without allowing for counter proposals. Effectively, the initiating agent has to pick from the presented contracts and cannot negotiate the price. The advantage of contract net is that it distributes computing, allowing the specific agent which started a contract net process to be responsible for evaluating bids and deciding based on its own rules which contracts to accept. It also separates internal agent information from one another, since agents only communicate through the defined contract net protocol and all calculations are done internally to each agent. Since the agents can change at every contract net cycle, there is no dependence on a specific agent. A system with more complex negotiation might lead to lower costs for the system; however, simple contract net is sufficient to demonstrate a distributed coordination framework.

Another factor in having a fully distributed system is the use of a directory service. A directory service allows agents to register themselves and publish their capabilities. By using a directory service, agents do not have to be aware of the other agents. For example, a load agent will look up sources in the directory every time it wants to secure a new supply contract. This allows for agents to be added or removed from the system at any time since agents are included in contract net negotiations once they register themselves with the directory service.

The coordination layer that the approach defines is the strategic layer above the real time layer. Because of the time required for a contract net interaction to complete, and since contracts are assigned in discrete time intervals, this coordination layer cannot address real time issues. The coordination layer allows for the distributed agents to plan how resources should be applied for satisfying demand. The actual operation of the system components self regulates through negative feedback since the system cannot produce more energy than is consumed. Fig 5 shows the proposed contract-net message flowing.

C. Checking Reliability of MicroGrid with PowerWorld Simulator

Once the market is simulated, before the scheduling is proposed, the reliability of the MicroGrid is checked with PowerWorld Simulator [15] in order to ensure that the scheduling does not undermine the reliability of the

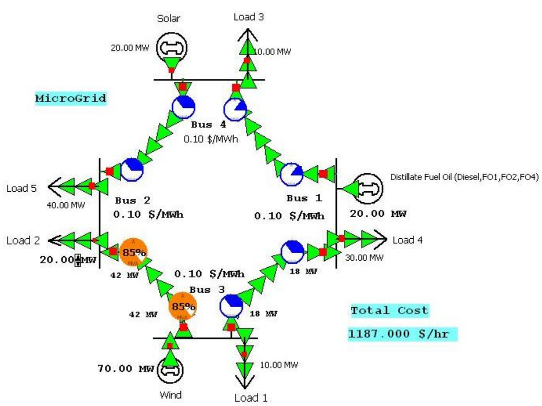

Fig. 6. PowerWorld Simulator snapshot

MicroGrid.

PowerWorld simulator is a commercial power system simulation package based on comprehensive, robust power flow solution engine capable of efficiently solving system up to 100000 buses, implementing the full Newton- Raphson method, the fast decoupled power flow and a DC power flow. It also allows the user to visualize the system through the use of animated diagrams proving good graphical information about the technical and economic aspects of the transmission network. It has several optional add-ons. OPF and SimAuto add-ons are used for this project.

The OPF provides the ability to optimally dispatch the generation in an area or group of areas while simultaneously enforcing the transmission line and interface limits. Simulator OPF can then calculate the marginal price (LMP) to supply electricity to a bus, while taking into account transmission system congestion. The advantages of the Simulator OPF over other commercially available Optimal Power Flow packages are ability to display the OPF results on system one-line diagrams and contour the results for ease of interpretation and users can export the OPF results to a spreadsheet, a text file, or a PowerWorld AUX file for added functionality.

SimAuto [15] is an automated server (COM interface), enabling the user to access the functionalities from a program written externally by COM server. Even though Java does not have COM compatibility, Java platform integrates Java Native Interface (JNI) which is a standard programming interface for writing Java native methods and embedding the Java virtual machine into native application. The IBM Development Tool for Java-COM Bridge [16] is chosen to build a communication layer between Java and the Power World automation server.

Suppose the scheduling is congested, the MGCC would employ the use of the PowerWorld Simulator OPF to mitigate congestion. The purpose of the OPF is to minimize the cost function by changing system controls and taking into account both equality and inequality constraints which are used to model the power balance constraints and various operating limits. It functionally combines the power flow with economic dispatch. In PowerWorld, the optimal solution is being determined using the primal approach of linear programming. Once congestion has been mitigated, the new network schedule and relevant network information will be extracted.

V. Results and Discussion

An agent-based approach for coordinating DER, using contract net as the coordination technique, has been developed and demonstrated by software simulation. Some potions of the output of the programming are given here to show the contract net protocol is successfully implemented.

```
StartAgent@NUS-ELESHC:1099/JADE: is launched.
Power1 is created.
Load1 is created.
Power1 started and registered with DF as Power Generator
Load1 started and registered with DF as Load
Power1: The list of Load in the network: Load1 Load2 Load3 Load4 Load5
MGCC is created.
Load1: The list of pGen in the network: Power1 Power2 Power3
MGCC started and registered with DF as MGCC Agent
Load1: The list of MGCC agents in the network:  MGCC
Load1: Sent to MGCC: SUBSCRIBE
Power1: The list of MGCC agents in the network: MGCC
Power1: Sent to MGCC: SUBSCRIBE
MGCC: The list of pGen in the network: Power1 Power2 Power3
MGCC: The list of Load in the network: Load1 Load2 Load3 Load4 Load5
MGCC: Message received: Load1: SUBSCRIBE
MGCC: Message received: Power1: SUBSCRIBE
Load1: Message received: MGCC: AGREE
Power1: Message received: MGCC: AGREE
Load1: Message received: MGCC: CFP
Power1: Message received: MGCC: CFP
MGCC: Message received: Load1: PROPOSE
MGCC: Message received: Load1: Bid Owner: Load1
                               Quantity: 10.0MW
                               Price: 11.0cts
```

MGCC: Message received: Power1: PROPOSE
MGCC: Message received: Power1: Bid Owner: Power1
Quantity: 70.0MW
Price: 10.5cts
MGCC: Sent RESULTS: Power1
Load1: Message received: REJECT-PROPOSAL
Load1: Message received: Unsuccessful at bidding!
Power1: Message received: ACCEPT-PROPOSAL
Power1: Successful bid at: Bid Owner: Power1
Quantity: 70.0MW

Further, the different scenarios of double sided bidding PoolCo market are simulated and results are given in the Table 1. Scenario1 has excess demand and scenario 2 has excess supply at the MCP and supply and demand are matched at the MCP for scenario 3. The excess demand and excess supply at MCP for corresponding scenarios are indicated through bolded numbers.

TABLE I
INPUT S AND OUTPUTS OF SIMULATIONS

	SCENARIO 1				SCENARIO 2				SCENARIO 3			
AGENTS	INPUT		OUTPUT		INPUT		OUTPUT		INPUT		OUTPUT	
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
PGEN1	11	70	11	70	11	70	11	**65**	11	70	12	70
PGEN2	12	20	NA	NA	12	20	NA	NA	12	20	NA	NA
PGEN3	10	25	11	25	10	35	11	35	10	20	12	20
LOAD1	11	10	11	**5**	11	10	11	10	11	10	NA	NA
LOAD2	12	20	11	20	12	20	11	20	12	20	12	20
LOAD3	10	10	NA	NA	10	10	NA	NA	10	10	NA	NA
LOAD4	14	30	11	30	14	30	11	30	14	30	12	30
LOAD5	13	40	11	40	13	40	11	40	13	40	12	40

P- Price in cents and Q- Quantity in kW.

VI. CONCLUSION AND FUTURE RESEARCH

Distributed energy resource can be made scalable and robust with a coordination strategy that allows for easily adding or removing energy resources. An energy node can expand as demand increases and can change configuration easily. Distributed coordination, a potential method to realize these benefits, can be implemented by using multi-agent technology. The software simulation demonstrates that it is possible to apply a distributed coordination approach to coordinating distributed energy systems at the strategic level. The distributed system is also self-organizing, allowing agents to be added or removed at any time, without any dependency on a specific agent. By using the appropriate software architecture, distributed coordination seems like a likely strategy to realize the benefits of distributed energy systems.

Ultimately, the concept of multi agent based distributed coordination will need to be connected with an actual hardware implementation to demonstrate a complete agent based solution for distributed energy resources management. In order to achieve it, the future research will be focused on intelligent MicroGrid operations such as load forecasting, forecasting of RES power production, economic resource scheduling and demand side management (DSM), which can be added on this MicroGrid modeling in future.

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