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Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system

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ABSTRACT

This paper proposes a multi-agent system for energy resource scheduling of an islanded power system with distributed resources, which consists of integrated microgrids and lumped loads. Distributed intelligent multi-agent technology is applied to make the power system more reliable, efficient and capable of exploiting and integrating alternative sources of energy. The algorithm behind the proposed energy resource scheduling has three stages. The first stage is to schedule each microgrid individually to satisfy its internal demand. The next stage involves finding the best possible bids for exporting power to the network and compete in a whole sale energy market. The final stage is to reschedule each microgrid individually to satisfy the total demand, which is the addition of internal demand and the demand from the results of the whole sale energy market simulation. The simulation results of a power system with distributed resources comprising three microgrids and five lumped loads show that the proposed multi-agent system allows efficient management of micro-sources with minimum operational cost. The case studies demonstrate that the system is successfully monitored, controlled and operated by means of the developed multi-agent system.

1. Introduction

As the backbone of the power network, the electricity grid is now at the focal point of technological innovations [1–3]. Utilities around the world are committing billions of dollars to the installation of intelligent systems and applications into their existing infrastructure to make them more reliable, efficient and capable of exploiting and integrating alternative sources of energy. The intelligent grid achieves operational efficiency through distributed control, monitoring and energy management. In addition to enabling utilities to bring renewable sources of energy into the mainstream, the intelligent grid's most immediate impact is to allow efficient and optimal use of utilities' existing assets through demand response and peak shaving [1]. An important goal of intelligent grid is to design for resiliency and autonomous re-configurability in the electric power grid to guard against man-made and natural disasters. One way to assure such self-healing characteristics in an electric power system is to design for small and autonomous subsets which can be called microgrids of the larger grid.

The penetration of distributed generation (DG) is one of the outcomes of the deregulated energy environment [4–6] in addition to the gradual transition from centralized power generation to distributed generation. DG sources comprise several technologies, like diesel engines, micro-turbines, fuel cells, wind turbines and photovoltaic sources. The capacity of DG sources varies from a few kWs to MWs. Microgrids [2] that can be defined as low voltage intelligent distribution networks comprising various distributed generators, storage devices and controllable loads, can be operated as interconnected systems with the main distribution grid, or as islanded systems if they are 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 are similar to traditional low voltage (LV) local distribution networks that provide electricity. Microgrids can enhance local reliability, reduce emissions, improve power quality by supporting voltage, and potentially lower the cost of energy supply if they are properly deployed. Concept of integrated microgrids comes into picture when many microgrids are built at a LV network. Different microgrids could have differ types of load and energy sources even at same LV network. Therefore, it is possible to get even more benefits with a proper resource sharing between the microgrids than that from a single microgrid.

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Concurrently, the power system researchers focus on the potential value of multi-agent system (MAS) technology to the power industry [1,7–11]. These recent research works have shown that MAS is one of the best technologies for introducing distributed intelligence in power systems. Coordinating behaviour of autonomous agents is a key issue in agent-oriented technique, which leads the MAS towards the system goal. As MAS is becoming a significant and growing interest in power engineering, it is very important that the power engineering community need to consider the standards, tools, supporting technologies, and design methodologies available for implementing a MAS solution for power engineering problems [12,13].

Energy resource scheduling is an important optimization task in the daily operation planning of any power system, which is typically handled by power system managers. Energy resource scheduling has two stages: unit commitment (UC) and economic dispatch (ED). Unit commitment [14,15] can be defined as finding of ON/OFF statuses of power production units over a daily to weekly time horizon, while respecting various generator and system constraints. Typically, objective of the problem is to minimize the costs associated with energy production, and start-up and shut-down costs. The resulting problem is a large scale nonlinear optimization problem for which, there is no exact solution technique. The solution to the problem can be obtained only by complete enumeration, often at the cost of a prohibitively long computation time requirement for realistic power systems. Therefore research endeavours have been focused on efficient near-optimal UC algorithms, which can be applied to modern power systems. Economic dispatch [14] calculates the operating power levels of each committed units based on the generator cost functions submitted by all generators prior to the dispatch decision.

Most of the research work on unit commitment has been done in centralized approach [15–17], whereas very little work has been done in distributed approach [18,19]. In this paper, energy resource scheduling using a distributed multi-agent approach is proposed for islanded power systems with distributed resources, which could be a part of a big power system network. The islanded power systems with distributed resources consists of several microgrids and lumped loads. The internal loads of the microgrids and lumped loads could be different types of loads such as industrial, commercial and residential loads. Although it is assumed that the proposed system would be implemented on the distributed servers, several agents were placed onto single computer system for simplicity in the prototype system.

The proposed MAS approach in this paper has been used to simulate an islanded power system with distributed resources consisting of three microgrids and five lumped loads. Lagrangian Relaxation with Genetic Algorithm (LRGA) [16,20] is used for scheduling of energy sources in each microgrid individually. In this case, each microgrid has different types of distributed energy resources (DER) and internal loads. The lumped loads represent the sum of loads in the areas, which are restricted by separate management authorities. This is a similar case as power systems in countries like Indonesia, Philippines and India, where mining industries are built in rural area. In the areas, as there are no main power supply available, most of the power system companies compete to setup their microgrids.

The structure of the remaining paper is as follows: Section 2 provides background knowledge for understanding the concepts of MAS. Section 3 explains briefly about implementation of the MAS. Section 4 formulates the problem and Section 5 gives an overview of the proposed methodology. Section 6 describes the power system with distributed resources used in this paper and contains the data for the simulation. Section 7 presents the results and discussion. Finally, it is concluded in the 8th section.

2. Multi-agent system approach

2.1. Multi-agent system

Multi-agent system (MAS) is one of the most exciting and fastest growing domain in agent oriented technology, which deals with modeling of autonomous decision making entities. MAS modeling of a microgrid is one of the best choice to make much intelligent power system, where each necessary element is represented by an intelligent autonomous agent. It provides a platform to use combination of artificial intelligence and mathematical tools to decide agents' optimal actions. In this paper, each power source and controllable load is modelled as an autonomous agent and a common communication interface is provided for them and all the other agents representing the other components in the network.

The fundamental element of multi-agent system is an intelligent agent [21], which has the three typical characteristics, namely, reactive, proactive and social abilities. Reactivity of an intelligent agent is the ability to recognize any changes in its environment and react with corresponding actions based on the changes and the goal of the agent. Pro-activeness of intelligent agent displays goal oriented behaviours. The goal is objective of agent, which set to achieve system goal with the other agents. Social ability of an intelligent agent is the ability to interact with the other intelligent agents in its environment. Social ability connotes more than simple passing of data between different software and hardware entities, something many traditional systems do. It connotes the ability to negotiate and interact in a cooperative or competitive manner. Together with these characteristics, some of the characteristics of intelligent agents in a microgrid are explained below in details.

1. Agents are capable of reacting in the environment. It means, agents are capable to change their environment by their 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 behaviour of other agents.
2. Agents communicate with each other. This is a part of their capability to react in the environment. For instance, agents controlling micro-sources communicate with the market operator and the other agents in order to negotiate bids in the internal microgrid market.
3. Agents have a certain level of autonomy. It means, agents can take decisions driven by a set of tendencies without having to take instructions from a central controller or commander. The autonomy of each agent is related to its resources and goals. For example, the amount of available fuel, in case of a fuel based production unit.
4. Agents represent the environment. Each agent not only knows its own status but also has knowledge about the statuses of the neighbouring agents or sub systems via conversation with the other agents.
5. Agents have certain behaviours and tend to satisfy certain objectives using their 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 behaviours. As a consequence, the behaviours of each agent are formed by its goals.
6. Similar agents can have different behaviours. For instance, an agent that controls a battery system aiming to provide uninterruptible supply to a load, can have different behaviours from those of a similar battery system.

As a whole, the characteristics and behaviours of individual agents in the multi-agent system are formed by the system goal, which generally optimizes control and managerial operations of the system.

2.2. Advantages of MAS approach

Multi-agent system approach has several advantages over the traditional approaches for management and control of microgrids [7,9,22]. Some of the important advantages of the MAS approach are given below.

1. Unit autonomy: This is a basic characteristic of an agent. Depending on the goals of agents, the agents in the microgrid can behave autonomously in their environment, which could be cooperative or competitive.
2. Reduced need for large data manipulation: Typically, the information should be processed locally and agents exchange their knowledge. In this way, the amount of data exchanged is limited and so is the demand for an expensive communication network. It is common in traditional distributed computing also.
3. Increased reliability and robustness of the control system: In case one of any controller fails, the other agents adapt and continue the system functions.
4. Openness of the system: Multi-agent system allows manufacturers of DER units or loads to embed a programmable agents in the controllers of their equipments according to some rules. In this way, the required "plug and play" capability for installing future DER units and loads can be provided.
5. Learning of agents: Agents can learn from their past actions and behaviours. Agents update their decision making rules based on the effectiveness of their current rules to provide better performance.

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

2.3. Technical challenges and problems

As MAS is becoming a significant and growing interest in power engineering, it is important to identify the key technical problems and challenges that are needed for adoption of multi-agent system effective within the field and how to overcome them. Challenges include selection of multi-agent platforms, designing of intelligent agents, agent communication languages and ontologies, industrial standards and security of multi-agent system. Selection of multi-agent platforms is an important challenge because there are number of multi-agent system platforms exist in research and development. However, judicious selection is required to ensure long-term compatibility and robustness. A good platform should be flexible, extensible and open architectures with standards-adherence. Further, agents should be able to interact with each other irrespective of the platform they run on. Designing of intelligent agent is another challenge. As there are several concrete architectures available in the literature, proper designing of intelligent agents for power engineering applications is also a challenging task. Intelligent agents should be designed with their typical characteristics such as reactivity, pro-activeness and social ability. Developing and following a set of common international standards for multi-agent system designing is also a challenging task. Agent communication languages and designing of ontologies should be based on common standards. On the other hand, it is very difficult to interconnect several multi-agent systems together in future. At this moment, Foundation for Intelligent Physical Agents (FIPA) [23] international standards are agreed by most of the multi-agent system developers. A key aspect of using agent-based technology is that all agents within power engineering applications should be able to cooperate and interoperate. The aspect should be independent of the individual developer but based on the power engineering community standards. Therefore, the community must agree on the adoption of appropriate agent communication language standards. Security of multi-agent systems that is another challenging task, is a key concern due to the peer to peer nature of multi-agent system. If agents join with an agent community, there must be measures in place to determine the level of trust between agents and the security of messaging. It is even more concern when there are mobile agents in the system.

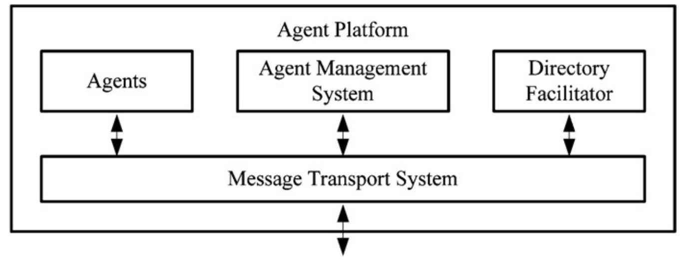

Fig. 1. FIPA agent management reference model [23].

3. Implementation of multi-agent system for a power system with distributed resources

3.1. Selection of multi-agent platform

Agent platform is a software environment, where software agents run. There are number of multi-agent system platforms available now. However, judicious selection is required to ensure long-term compatibility and the required robustness for online applications. In this project, JADE (Java Agent DEvelopment) framework that conforms to FIPA standards for intelligent agents, is used. JADE is also used as the runtime environment in which agents execute, thereby masking 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 in turn executes within a Java Virtual Machine (JVM). Agent lives in a container, and a collection of containers make up a platform. A platform encompasses all the containers within an agent system and therefore can span multiple computers.

In this implementation, 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. As shown in Fig. 1, JADE platform provides a set of functions and classes to implement agent functionality, such as agent management service, directory facilitator and message passing services. Agent management service (AMS) is responsible for managing the agent platform, which maintains a directory of Agent Identifiers (AIDs) and agent states. 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) that is responsible for delivering messages between agents, provides services for message transportation in the agent system.

3.2. Generic architecture of an agent

Fig. 2 shows the generic architecture of an agent in the developed MAS. Knowledge base modules are implemented with rules

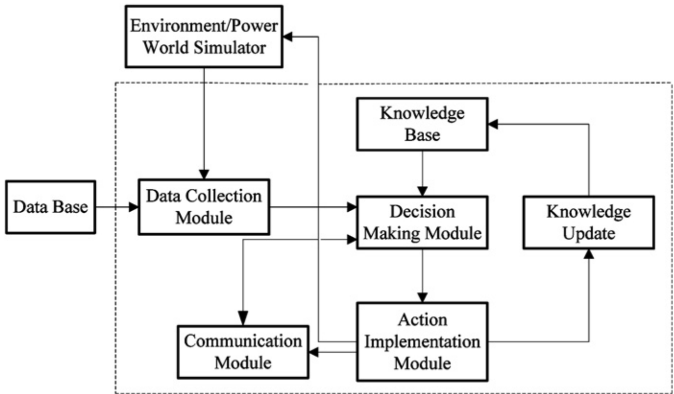

Fig. 2. Generic architecture of a developed agent.

base systems and there is no learning of agents (Knowledge update) implemented at this moment. It will be implemented in the future if there is needed of learning of any agent for better performance. Details implementation of decision making module is explained in the proposed methodology section and agent communication is implemented according to FIPA standards. Data collection from and to power world simulator is developed with EZJCOM software, which interfaces JADE/Java and Sim-Auto of power world simulator.

3.3. Implementation of the multi-agent system

A generic software packages have been designed and developed for the MAS implementation. Agents, behaviours, ontology, tools and power system are the main software packages developed in this framework. The agents package consists of different types of agents and the behaviour package contains tasks assigned to the agents. The ontology package specifies a set of vocabulary for agents' communication and the tools package has a collection of tools, which are used by the agents for managing and processing the microgrid managerial functions. Finally, the power system package comprises of data structures used to represent the state of the power system with distributed resources.

Coordinating behaviour of autonomous agents is a key issue in multi-agent system for agents' social abilities. At a low level of agent management system, agents in each microgrid communicate each other cooperatively to minimize the production cost of their microgrid. At the top of the agent management system, microgrids and lumped loads communicate each other competitively to sell or buy electricity. As agent technology has matured, there are a number of different communication languages available for inter agent communication. FIPA Agent Communication Languages (ACL) has been used in this project. A FIPA-ACL message contains several fields [23]. The first and only mandatory field in the message is *performative* field that defines the type of communicative act or speech act. The important *performatives* used in the implementation are shown in Fig. 8. The content of a message comprises two parts: content language and ontology. The content language defines syntax, or grammar, of the content. The semantics or lexicon is drawn from the ontology. Ontologies provide a way to structure information for several agents in the multi-agent system to understand the semantics of knowledge and to agree upon the terminologies used in agent communication.

Since JADE's libraries were utilized to implement the MAS, agents, behaviours and ontology were implemented directly as extensions of corresponding JADE's classes. This project did not concentrate to implement and design agents, behaviours, and ontology from scratch. Similarly, standard FIPA-SL content language was adopted exactly for agents' communication. As JADE provide flexibility to develop own ontology together with extension of JADE ontology, a set of ontologies has been created to structure information transferred between agents. Concepts, predictors and agent actions are the basic components of ontologies. Concepts, as the name suggests, model domain concepts such as microgrid, distributed resources and features of each element. Predicates specify concept relationships, which can be evaluated as true or false. For instance, statuses of DERs and loads. An action is a type of concept specifically for communicative, where agents discuss an event happening. For instance, ON/OFF of production unit or charging/discharging of storage system.

4. Problem formulation

Fig. 3 shows an islanded power system with distributed resources, which is considered for the simulation studies in this paper. This is an islanded system from the main power grid and consists of three microgrids and five lumped loads. Each microgrid operates as an independent power producer and each lumped load also has separate management system. While satisfying their own demands, microgrids bid in a competitive energy market to sell electricity to network.

4.1. Scheduling of a microgrid

Scheduling of a microgrid is similar to typical unit commitment problem, which determines the statuses (ON/OFF) of power generating units for each time period in the scheduling horizon, as well as the power output levels, subject to the system and generating

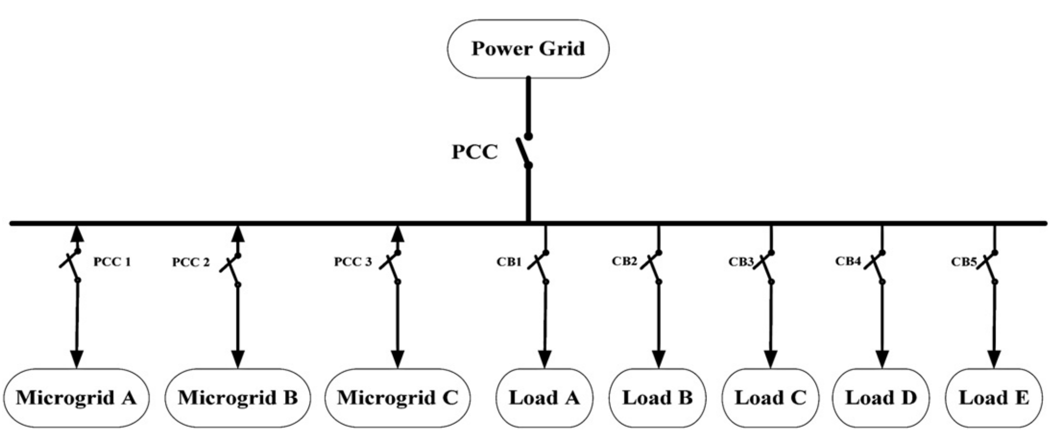

Fig. 3. Schematic diagram of an islanded power system with distributed resources.

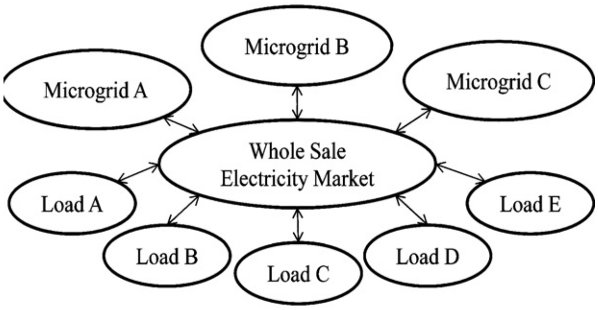

Fig. 4. Energy market players of the case study.

units' operating constraints. Objective of the scheduling problem is the minimization of the total production cost over the scheduling horizon. Therefore, the objective function is expressed as the sum of fuel cost and start-up costs of the generating units. Mathematically, the scheduling problem can be formulated as is the references [20].

4.2. Scheduling of integrated microgrid

Scheduling of the integrated system is proposed based on PoolCo [4] market, which is a wholesale energy market consists of competitive independent power producers, vertically integrated distribution companies load aggregators and retail marketers. PoolCo does not own any part of the generation or transmission utilities. The main task of PoolCo is to centrally dispatch and schedule generating units in its service area within its jurisdiction. In a PoolCo market operation, buyers submit their bids to the pool in order to buy power from the pool and sellers submit their bids to the pool in order to sell power to the pool. All the generators have right to sell power to the pool but they are not allowed to specify customers. Similar, all the loads have right to buy power from the pool but they are not allowed to specify the suppliers.

As shown in Fig. 4, each microgrid and lumped load submits its bids to the PoolCo, where these bids are summed up and matches interested demands and supplies. Market operator (MO) performs the economic dispatch and produces a single spot price for electricity within the system. This price is called as Market Clearing Price (MCP) which is typically the highest price in the selected bids for the simulation hour. Winning microgrids are paid the MCP for their successful bids while successful bids of loads are obliged to purchase electricity at MCP. The typical PoolCo market clearing algorithm as explained in [9] is implemented for the scheduling.

5. Proposed methodology

This paper proposes a MAS for energy resource scheduling of power system with distributed resources, which has several microgrids and lumped loads interconnected each other. The algorithm behind the proposed MAS has three stages. The first stage is to schedule each microgrid in the network individually to satisfy its internal demand. This step helps to find out possible bids of microgrids. The next stage is to find out the possible bids of each microgrid for exporting power to the network and compete in a wholesale market to provide power for lumped loads. In the stage, the market outcomes for each scheduling hour is known. The final stage is to reschedule each microgrid individually to satisfy its total demand. The total demand of a microgrid is the addition of internal demand and the external demand, which is from the outcome of wholesale energy market. Flowchart of the proposed algorithm is given in Fig. 5.

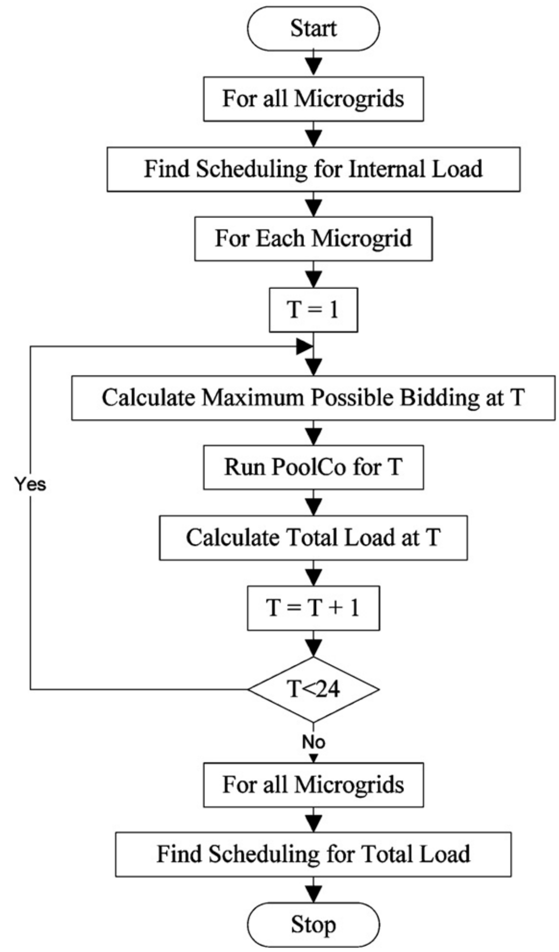

Fig. 5. Proposed scheduling algorithm behind the developed MAS.

The algorithm that used in [20] has three steps, is employed to schedule individual microgrids. The first step of the algorithm is to set up initial feasible solution for UC of thermal units, where the total thermal energy necessity for the system is minimized. The second step is to solve UC problem of thermal units, which is typical traditional UC problem. Several algorithms were developed and used to solve this problem. In this paper, Lagrangian Relaxation with Genetic Algorithm (LRGA) is used to solve the problem. This hybrid technique provided high quality solution and better convergence within a small computation time. The final step is to optimize the renewable sources-thermal units dispatch based on the results of UC of thermal units.

5.1. Distributed control system

It is very important that the integration of micro-sources into the low voltage grids, and their relationship with other sources in the other microgrids as well as the medium voltage network upstream be done in a manner to optimize the operation of the system [7,9,24]. A distributed control strategy, which comprises three critical control levels as shown in Fig. 6, is proposed for the integrated microgrid application.

Local micro-source controllers (MSC) and load controllers (LC): For each micro-sources, there is a local micro-source controller, which has autonomy to perform local optimization of the micro-source's active and reactive power production. A local load controller is installed at each controllable load to provide load control capabil-

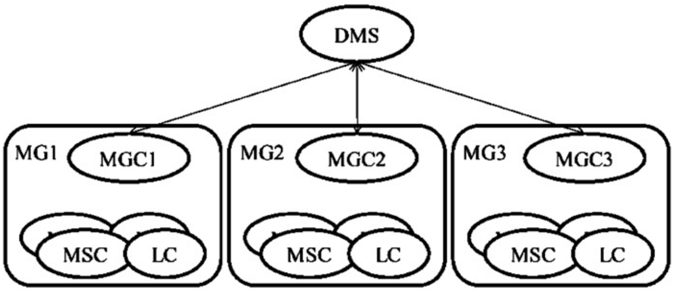

Fig. 6. Control architecture of integrated microgrids.

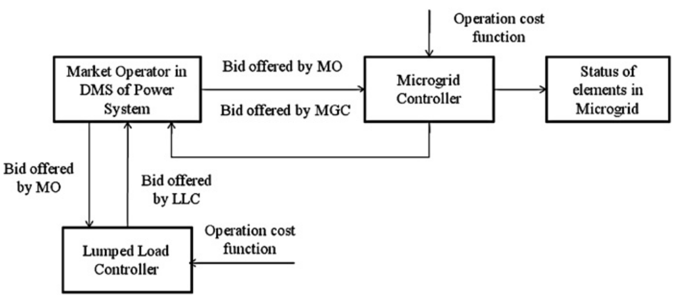

Fig. 7. Exchange of bidding information.

ities following instructions from the MGC or during load shedding management.

Microgrid controller (*MGC*): MGC is responsible to provide system load forecasts and to optimize the operation of microgrids by coordinating the MCs and LCs in such a way that the economics and security of the system is taken into account.

Distribution management system (*DMS*): DMS works together with the MGCs in order to operate the overall distribution system in economical and secure manner. It consists of some functional elements such as distribution network operator (DNO) and market operator (MO). DNO that is similar to ISO in the deregulated power system, is responsible for the technical operation in low and medium voltage area, where the microgrids exist and MO that is similar to PX in the deregulated power system, is responsible for the market operation of the area.

5.2. Bidding strategy

During the market operation, the MO receives bids from all microgrid controllers (MGC) and all lump load controller (LLC). The price signals from microgrid controllers reflect the payment asked by the microgrid for producing their kW output and the price signals from lump load controllers reflects the amount to be paid to the load for providing load shedding respectively. Fig. 7 shows the exchange of bidding information.

Lump local controllers derive the bidding price and quantity from the predetermined operational cost function and its operating point. The microgrid controllers find their bids on the operating cost functions of power sources in the microgrid and the internal demand of the microgrid. The bidding price depends on above factors as well as other factors such as market forecast and owners preferences. Methodology for finding bidding quantities can be extended from bidding strategy [4] of single thermal unit, which is as follows:

Bidding curve of a generator [4] with a quadratic cost function $C(P) = a + bP + cP^2$ is given by,

$$m = \frac{\rho_g - b - 2cP_O}{c(P - P_O)} - 1 \tag{1}$$

where the slope m defines the bidding strategy, which is 0 for bidding at incremental cost and 1 for bidding at marginal cost. P_O represents the sum of bilateral contact quantity and its own load. In this paper, since bilateral contracts were not considered, this represents only the latter. In this paper, $m = 1$, bidding at marginal cost strategy is considered and it is assumed that each microgrid and lumped load has market price forecasting facilities. The bidding price is taken as the individual forecasted market price. Therefore, the corresponding available power at each individual generators is calculated by,

$$P = \frac{\rho_g - b - 2cP_O}{c(m + 1)} + P_O \tag{2}$$

Bidding quantity (BQ) of the microgrid can be calculated as a sum of the total available power of all generators in the microgrid.

6. Simulation and simulation data

The methodology of energy resource scheduling is tested on an islanded power system with distributed resources which consists of integrated microgrids and lumped loads. Three microgrids and five lumped loads are in the system under the study. The simulation was carried out for a typical day. Details of distributed energy resources in each microgrid are given in Table 1.

It is assumed that each microgrid and lumped load has its own forecasting facility to forecast hourly demands and the market price. Table 2 shows the forecasted demand and market prices for each of them for 24 h of a typical day. In addition, the reserves for each microgrid are considered as 10% of hourly internal demand of microgrids.

It is considered that each battery banks, PV systems and wind plants are identical and corresponding data of the elements are given in [20]. The power from the renewable-battery system is calculated from the meteorological data for the day as in [20]. Details of thermal units are given in Table 3. Various constraints on generating units and system constraints discussed in [20] were included in the simulations.

6.1. Flow of multi-agent simulation

The multi-agent system can be started up via an agent launch pad by which all the administrative agents such as PoolCo agent and its subordinate agents, security manager agent and its subordinate agents, power system manager agent, microgrid agents and its subordinate agents, lumped load agents are launched. All agents execute their own thread to initialize them. When all the parameters of the agents are properly initialized, each agent will autonomously register itself with the DF as its first task.

Fig. 8 shows the important *performatives* and messages of communication of agents. For simulating the market, the agents

Table 1
Details of DERs in the microgrids.

Microgrid	Thermal units	PV systems	Wind plants	Maximum renewable penetration	Battery banks
Microgrid A (2 MW)	12 (Unit 1–Unit 12)	3 × 360 kWp	3 × 140 kWp	1000 kW	1 × 500 kW, 2.5 MWh
Microgrid B (1.5 MW)	11 (Unit 2–Unit 12)	2 × 360 kWp	2 × 140 kWp	750 kW	1 × 500 kW, 2.5 MWh
Microgrid C (1 MW)	10 (Unit 3–Unit 12)	1 × 360 kWp	1 × 140 kWp	500 kW	1 × 500 kW, 2.5 MWh

Table 2
Forecasted demands and forecasted market price (MP).

Hour	MG A		MG B		MG C		Load A		Load B		Load C		Load D		Load E	
	Load	MP	Load	MP	Load	MP	Load	MP	Load	MP	Load	MP	Load	MP	Load	MP
1	1000	29.8	850	29.7	550	30.0	400	23.7	400	24.0	650	24.2	240	24.5	400	24.7
2	1030	29.9	860	29.9	570	30.2	450	23.8	400	23.9	670	24.1	260	24.4	410	24.6
3	1050	30.0	870	30.1	580	30.4	510	23.9	420	23.9	680	24.0	270	24.3	410	24.5
4	1070	30.1	880	30.3	600	30.6	520	24.0	440	24.0	600	24.1	310	24.2	420	24.4
5	1090	30.2	890	30.5	620	30.8	580	24.1	420	24.1	620	24.1	330	24.1	430	24.3
6	1150	30.3	900	30.7	650	30.8	600	24.2	430	24.2	650	24.2	340	24.2	430	24.2
7	1300	30.4	1020	30.9	730	30.6	560	24.2	470	24.3	630	24.3	330	24.3	460	24.3
8	1400	30.5	1150	30.9	800	30.4	500	25.0	400	28.0	600	26.0	350	27.5	480	28.5
9	1640	30.6	1300	30.7	870	30.2	460	27.0	450	29.0	670	28.0	360	29.0	560	28.5
10	1700	30.7	1400	30.5	900	30.0	410	28.0	440	28.5	600	28.5	350	30.0	560	29.0
11	1870	30.8	1480	30.3	990	29.8	370	29.5	480	29.0	690	29.5	350	29.0	570	30.0
12	1870	30.9	1450	30.1	940	29.8	360	29.5	450	29.0	640	29.5	350	29.0	560	30.0
13	1850	30.9	1450	29.9	910	30.0	400	30.0	450	30.0	610	30.0	340	31.0	560	30.0
14	1800	30.8	1430	29.7	910	30.2	460	30.0	430	30.0	610	30.0	340	31.0	560	30.0
15	1720	30.7	1420	29.7	900	30.4	470	29.5	470	30.0	600	30.0	340	30.5	570	30.0
16	1700	30.6	1410	29.9	890	30.6	500	29.5	400	30.0	600	30.0	330	30.5	510	30.0
17	1650	30.5	1400	30.1	870	30.8	470	29.5	460	30.0	670	30.0	350	29.5	570	30.0
18	1630	30.4	1350	30.3	860	30.8	460	29.5	450	30.0	660	30.0	350	30.0	560	30.0
19	1550	30.3	1330	30.5	850	30.6	460	29.5	430	30.0	650	29.5	300	30.0	560	29.0
20	1450	30.2	1300	30.7	850	30.4	400	29.5	440	30.0	650	29.8	350	30.0	500	29.0
21	1350	30.1	1270	30.9	760	30.2	380	29.0	460	29.5	660	29.5	360	29.0	480	29.5
22	1200	30.0	1200	30.9	630	30.0	360	27.0	430	29.5	630	29.5	360	27.5	460	29.5
23	1150	29.9	1050	30.7	600	29.8	400	26.5	470	27.0	640	27.0	370	27.0	440	26.5
24	1050	29.8	910	30.5	570	29.8	390	26.5	420	27.0	670	27.0	370	27.0	420	26.5

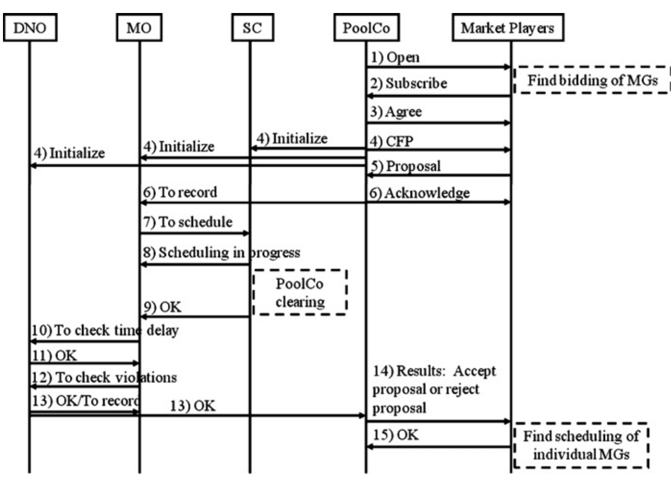

Fig. 8. Implemented coordination between agents.

coordinate among themselves in order to satisfy the energy demand of the system and accomplish the distributed control of the system. FIPA contract-net protocol [23] was chosen for the PoolCo market simulation. 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 contracts from the returned proposals in a fashion that minimizes cost or fulfils some other goal.

As soon as the agents register for security services, all further communication on the network is encrypted. When PoolCo is ready to communicate with all market player agents, in this project microgrid controllers and lumped load controllers, it broadcasts an OPEN message as shown in Fig. 8. All the player agents who wish to take part in this round of bidding, respond by sending a SUBSCRIBE message to subscribe PoolCo manager agent. In case of microgrid agents, MGC run LAGA UC algorithm to find the power settings of DER for their internal loads then find biddings of microgrids as explained in the bidding strategies section.

PoolCo then closes the subscription window after everyone in the network has subscribed or when the subscription date expires, whichever is earlier. Once everyone in the network has subscribed PoolCo manager agent, it issues an AGREE message to all agents who have signed up for the subscription service to confirm their subscription. When the AGREE message arrives, market player agents stop their own internal execution of whatever task they are involving with (e.g. receiving updates from the DF) to handle this newly arrived message, and record this correspondence in their internal message history database. All message exchanges are recorded by each and every agent in their own internal message history database. After that, they resume their operation at whatever they were doing before. At the same time, they continue to listen for new messages.

Table 3
Data of thermal units.

Parameters	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10	Unit 11	Unit 12
P_{max} (kW)	410	410	270	270	140	140	90	90	65	65	45	45
P_{min} (kW)	100	100	50	50	25	25	20	20	15	15	10	10
a (cts/h)	65	60	45	41	40	38	38	35	30	24	18	15
b (cts/kWh)	15.20	15.30	16.60	16.50	18.50	18.76	26.70	26.90	29.71	29.92	26.20	26.79
c (cts/kW^{2}h $\times 10^{-4}$)	5.2	6.1	21	21.1	42	53	8	12	9	13	24	31
Min Up (h)	5	5	3	3	2	2	2	2	1	1	1	1
Min Down (h)	5	5	3	3	2	2	2	2	1	1	1	1
Hot start cost (cts)	550	500	450	460	800	750	360	350	280	285	200	205
Cold start cost (cts)	1100	1000	900	920	1600	1500	720	700	560	570	400	410
Cold start time (h)	3	3	2	2	1	1	1	1	0	0	0	0
Initial status (h)	5	5	3	3	2	−2	−2	−2	−1	−1	−1	−1

After PoolCo manager agent sends out AGREE message to every agent who sent subscription message, PoolCo manager agent will also update its own internal message history database and proceed to prepare for a Call For Proposal (CFP) message broadcast. It then retrieves the list of subscribed agents in the network and sends a CFP message to all the subscribers. After PoolCo manager agent sends the CFP message, it also sends a message to its subordinate agents: DNO agent, MO agent and Schedule coordinator (SC) agent, asking them to initialize themselves and prepare for imminent auction and scheduling task. MO agent and SC agent are the entities used to model the internal division of PoolCo management. PoolCo agent is the front-door communication entity for representing the bidding system.

The CFP message arrives at the market player agents who have previously subscribed to the PoolCo service. Upon receiving this message, agents stop their execution as before and handle this newly arrived message. The player agents prepare themselves for bidding if they are interested to participate in the next round of bidding. At this stage, player agents submit their formal bids to the PoolCo agent, which processes these bids and sends the results to them. The submission of bids and replies from PoolCo agent are legally binding contracts. Buyers (i.e. lumped loads) who submitted bids to buy are legally obligated to buy the quantity of power at the bid price. The same conditions are also applied for sellers (i.e. microgrids). Agents who are interested in submitting bids have access to their internal bidding records. They will prepare the necessary parameters like price and quantity of electricity to buy or offer in the market, and the prepared parameters are encoded as a bid object. When encoding is completed, they send a PROPOSAL message to PoolCo agent with the bid object enclosed. PoolCo agent upon receiving the PROPOSAL message re-directs these messages to MO agent for recording. PoolCo agent only closes the proposal window after everyone in the network has submitted their proposals or proposal window expiry date is due, whichever is earlier. The proposal expiry date is by default one day after PoolCo agent sends out its CFP message. After the proposal window is closed, MO agent processes the bids collected. The whole set of data is hashed into a hashtable which is then sent to SC agent. At the same time, SC agent sends a message to the PoolCo manager agent to notify scheduling in progress.

SC agent has an algorithm which computes a data structure that represents the aggregated demand and the aggregated supply with respect to the price component using a rule based system. These data sets are processed to produce a single spot price, the MCP, at market equilibrium where the demand meets the supply. It also calculates the quantity of electricity transacted at this price. MO agent determines the successful buyer agents and seller agents in this round of bidding based on the MCP and quantity of electricity transacted. The whole set of data comprising of MCP, quantity of electricity transacted, list of successful buyer agents and seller agents, list of unsuccessful buyer agents and seller agents are then sent to PoolCo agent.

Once the market outcome is received, MGCs know the total individual demand of each microgrid which is the addition of internal demand and the corresponding market outcome. MGCs run LAGA algorithm and find the power settings of DERs for total demand of each microgrid. Before the scheduling is proposed, PoolCo agent sends the whole set of data to DNO agent for checking for any violation of technical constraints of the power system with distributed resources such as bus voltage and power flow limit of

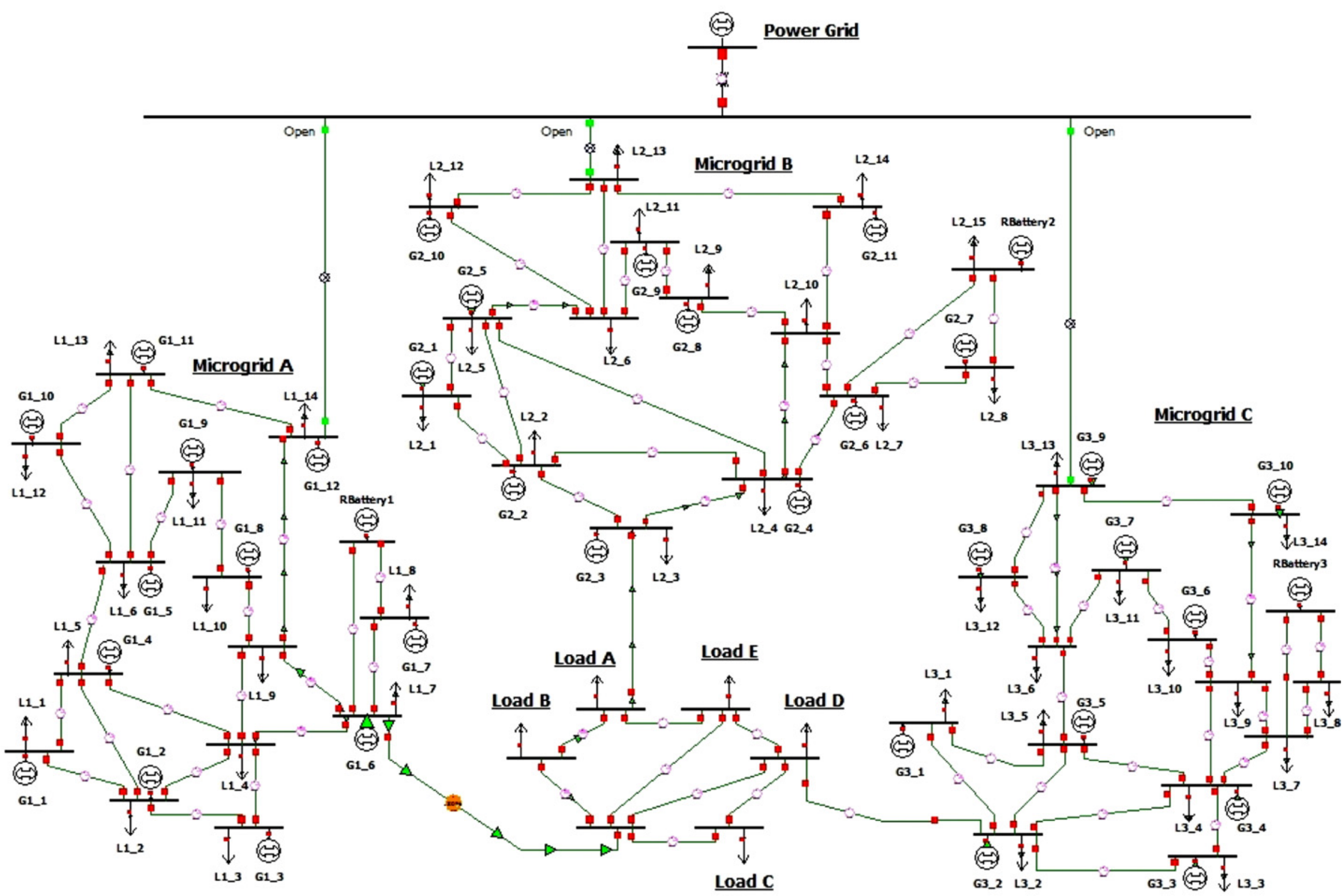

Fig. 9. Power world simulator snapshot of the case study.

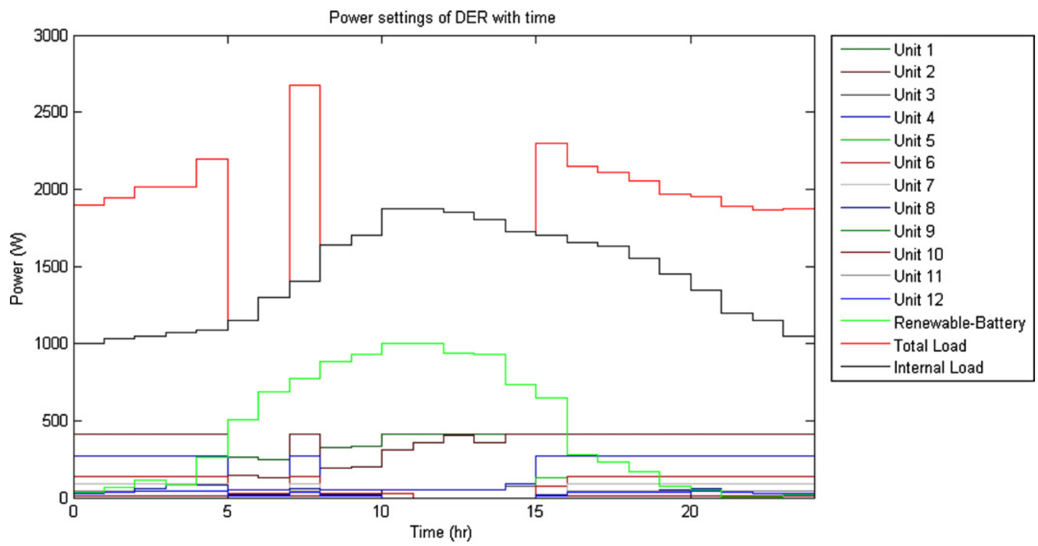

Fig. 10. Power settings of DER and demand of microgrid A.

transmission line and stability of the distributed resources. It is also checking time delay of biddings of the particular hour market. In this project, DNO uses power world simulator to check the violation of technical constraints with help of Optimal Power Flow (OPF) tool. Fig. 9 shows a snapshot of power world simulator for the test system used in this paper. 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. Once congestion has been mitigated, the new network schedule and relevant network information will be extracted from the power world simulator. Then whole set of data comprising of MCP, quantity of electricity transacted, list of successful buyer agents and seller agents, list of unsuccessful buyer agents and seller agents is sent to PoolCo agent.

After receiving this data, PoolCo agent extracts the relevant information and sends it to power system manager agent so that it can update the power system state. PoolCo agent also extracts the list of successful bidders from the set of data and sends a ACCEPT PROPOSAL message to successful bidders, embedded with details of the successful bids. PoolCo agent also extracts the list of unsuccessful bidders from the data and sends a REJECT PROPOSAL message to unsuccessful bidders. All bidders are notified of their bidding outcomes at the end of every bidding round. This whole process is one round of bidding in the PoolCo model for one time slot. Agents usually submit a complete schedule of 24 bids, representing their bids for the day-ahead market.

7. Results and discussion

Scheduling at integrated system level, PoolCo market simulation is proposed in this paper, where, microgrids compete for selling power. If bids submitted by the microgrids are too high, they have low possibility to sell their power. Similarly, lumped loads compete for buying power. If bids from lumped loads are too low, they have a smaller possibility to get the required power. In such a model, low microgrid bids and high lumped load bids would essentially be rewarded.

It is assumed in the project that each microgrid and lumped load have market price forecasting capability and they bid at their forecasted market prices. Therefore, any market player get success in the energy market, if they have a well forecasted market price. As explained in the bidding strategy, the bidding quantity of a micro-

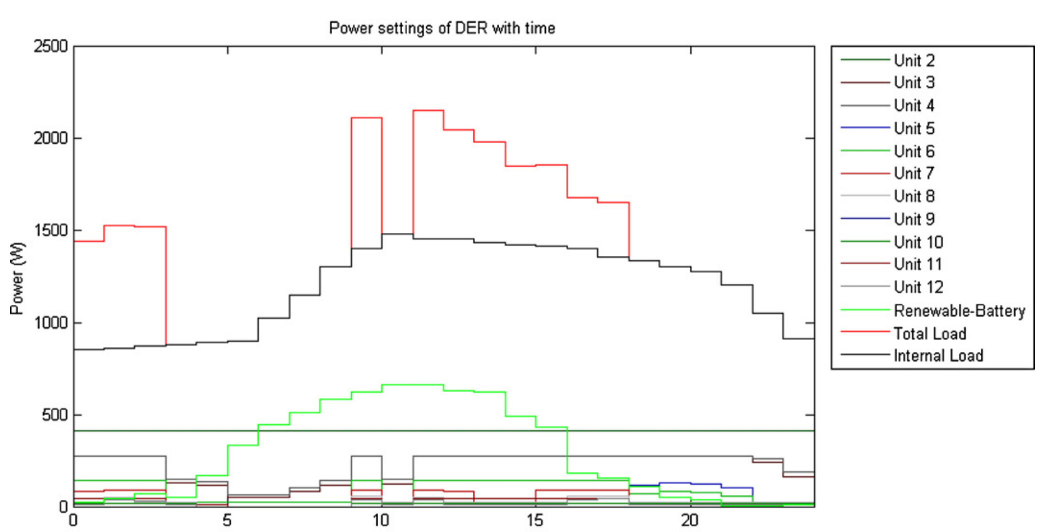

Fig. 11. Power settings of DER and load of microgrid B.

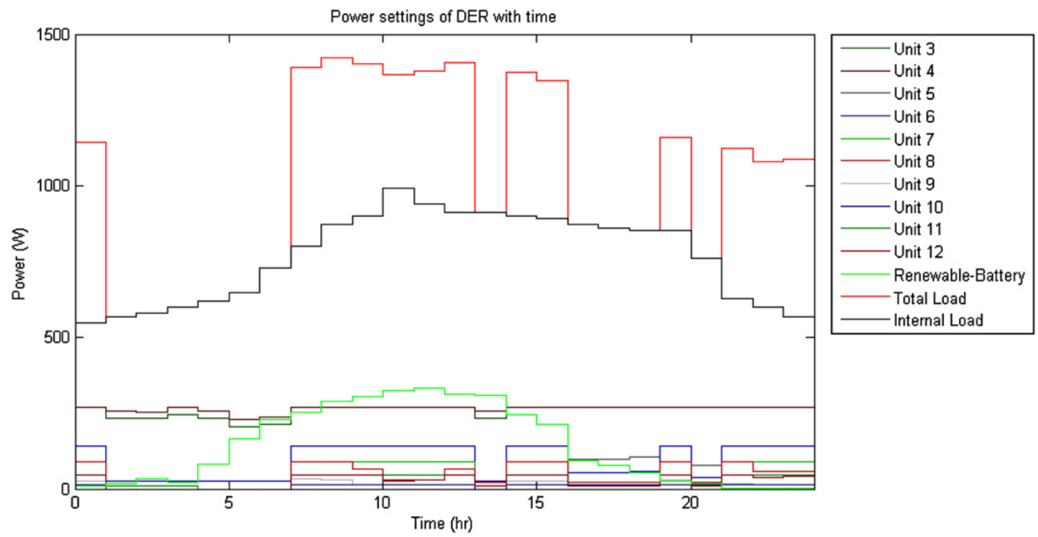

Fig. 12. Power settings of DER and load of microgrid C.

grid depends on forecasted market price, the amount of internal demand of the microgrid, initial states of DERs in the microgrid, as well as the uncertainty associated with the intermittent behaviours of DERs. According to the implemented market clearing algorithm, the successful bidding quantities of market players depend on the bidding quantities and bidding prices of all market players.

Figs. 10–12 show the unit commitment and power settings of each DER in each microgrid. Table 4 shows the bidding qualities (BQ) of microgrids which are calculated as explained in the bidding strategy section and successful bidding quantities (SBQ) which are the market outcomes from the PoolCo simulation. As seen from the results of the case study, no market player always gets success in all 24 h. The successful market players is different from hour to hour simulation, which is distributed among all market players. This reflects none of the market players in the case study has enough accurate market forecast price in all 24 h. On the other hand, a market player gets success in all 24 h.

The ultimate objective of the research is to design power system at distributed level optimally which contains several microgrids and integrated systems. The results verify the scheduling of an islanded power system with distributed resources. This is a fundamental function of optimal design and control of integrated as well as single microgrid. In order to verify the design and control of power system with distributed resources, several extensive cases studies and scenarios are needed to be done on both islanded systems and interconnected systems with main power grid.

The study case is a prevalent case in countries like Indonesia, Philippines and India, where mining industries are built in rural area. As there are no main power supply available in these area, most of the power system companies compete to setup their microgrids. Further, the future power system will consist of several small and autonomous microgrids at the distributed level. Therefore, a proper intensive studies on design, control and operation of distributed level system which contains more microgrid is necessary.

Table 4
Bid quantities (BQ) and successful bid quantities (SBQ) of market participants.

Hour	MCP	MG A		MG B		MG C		Load A		Load B		Load C		Load D		Load E	
		BQ	SBQ	BQ	SBQ	BQ	SBQ	BQ	SBQ	BQ	SBQ	BQ	SBQ	BQ	SBQ	BQ	SBQ
1	30.0	899	899	589	589	592	592	400	400	400	390	650	650	240	240	400	400
2	30.1	911	911	660	660	612	0	450	450	400	400	670	51	260	260	410	410
3	30.3	963	963	742	647	616	0	510	510	420	420	680	0	270	270	410	410
4	30.1	943	943	713	0	583	0	520	0	440	0	600	214	310	310	420	420
5	30.2	1106	1106	822	0	620	0	580	0	420	0	620	620	330	56	430	430
6	0.0	1280	0	969	0	670	0	600	0	430	0	650	0	340	0	430	0
7	0.0	1300	0	953	0	645	0	560	0	470	0	630	0	330	0	460	0
8	30.5	1273	1273	872	0	592	592	500	500	400	400	600	600	350	350	480	16
9	30.5	1121	0	782	0	552	552	460	0	450	0	670	0	360	360	560	192
10	30.5	1101	0	711	711	502	502	410	410	440	204	600	600	350	0	560	0
11	30.5	983	0	663	0	376	376	370	370	480	0	690	6	350	0	570	0
12	30.3	983	0	699	699	438	438	360	360	450	137	640	640	350	0	560	0
13	30.0	943	0	596	596	497	497	400	400	450	450	610	243	340	0	560	0
14	30.0	991	0	549	549	528	0	460	460	430	89	610	0	340	0	560	0
15	30.5	884	0	428	428	475	475	470	470	470	433	600	0	340	0	570	0
16	30.6	814	601	444	444	455	455	500	500	400	400	600	600	330	0	510	0
17	30.5	499	499	274	274	355	0	470	470	460	0	670	0	350	304	570	0
18	30.4	479	479	300	300	351	0	460	460	450	319	660	0	350	0	560	0
19	30.5	500	500	278	0	340	0	460	460	430	0	650	40	300	0	560	0
20	30.5	518	518	249	0	310	310	400	178	440	0	650	650	350	0	500	0
21	30.5	604	604	266	0	400	0	380	0	460	460	660	145	360	0	480	0
22	30.5	689	689	312	0	494	494	360	0	430	430	630	630	360	123	460	0
23	30.0	714	714	477	0	481	481	400	400	470	355	645	0	370	0	440	440
24	30.0	823	823	640	0	516	516	390	390	420	420	670	108	370	0	420	420

Studies on more microgrids, which is part of a bigger electrical network is a critical studies for the development of design and control of distributed system. Interaction between microgrids and interaction between microgrid and the main grid are the crucial tasks for better development of design and control schemes for not only integrated system but also single microgrid.

8. Conclusion

This paper presents multi-agent system for energy resource scheduling of an islanded power system with distributed resources. The system consists of a set of microgrids and lumped loads, which are electrically connected and complemented by a communication system. The multi-agent system is implemented in PIFA compliant JADE open source platform. The power system is successfully monitored, controlled and operated by means of the developed multi-agent system. The outcomes of simulations show the effectiveness of the proposed energy resource scheduling technique and the possibility of autonomous built-in simulation of power system with distributed resources.

The multi-agent system developed and implemented in this research is scalable, robust and easily reconfigurable. Therefore the developed multi-agent system can be easily extendable for managing and controlling any kind of power system with distributed resources by extending the functions of the agents and creating additional agents in the system.

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