Multi-Agent System for Market Based Microgrid Operation in Smart Grid Environment

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Abstract

Enabling electricity markets is one of main characteristics of a smart grid that integrates advanced sensing technologies, control methodologies, and communication technologies into current power distribution systems. Intelligent Multi-Agent System (MAS) that provides platform for modeling autonomous decision making entities in de-centralized fashion can be used to implement market based power system operation in smart grid. This paper presents development, and simulation of an intelligent multi-agent system based on IEEE FIPA (Foundation for Intelligent Physical Agents) standards in context of distributed smart grid. In particular, a multi-agent system is developed, and simulated for the market based operation of a microgrid in both islanded and grid-connected modes. Microgrid is an innovative control and management architecture at power distribution network, which makes easy to implement smart grid techniques. The simulation outcome shows that the proposed multi-agent system is an excellent platform for facilitating smart operation of microgrids.

Keywords:
Multi-agent system, Energy Market, Smart grid, Microgrid, Distributed energy resource, Distributed control and management

1. Introduction

Smart grid [1] is a vision of the future power systems and expected to exhibit some key characteristics such as consumer friendliness, hack proof self-healing, attack resistant, ability to accommodate all types of generation and storage options, enabling markets, high power quality, optimizing assets, and operational efficiency. Several economical, political, environmental, social, and technical factors have prompted the emergence of the smart grid. This intelligent grid is made possible by applying sensing, measurement, and control devices with two-way
communications to electricity production, transmission, distribution, and consumption parts of the power grid. Two-way communication is necessary for system users, operators, and automated devices to have the knowledge of grid condition in order to respond dynamically for the changes in grid.

Some of the key characteristics of smart grid such as high penetration of distributed power generation, demand side management, and market operations are being implemented in many current power distribution systems. Most of the current power distribution systems consist of distributed generation in the control and management architecture of microgrids. Microgrids [2,3] are low voltage distribution networks comprising various distributed generators, storage devices and controllable loads, which are operated either in grid-connected mode or in islanded mode. Microgrids enhance local reliability of the power grid, reduce emissions, improve power quality, and potentially lower the cost of energy supply. These enhancements denote the abilities of microgrid architecture for implementing smart grid techniques at power distribution network level.

Current approach of using a central SCADA system, and several smaller distributed SCADA systems is no longer sufficient for certain control operations of modern power distribution systems. An approach that provides adaptable local control and intelligent decision making is required. Multi-agent system [4] is a promising technology for implementing such a system because it provides a common communication interface for all elements, and has the potential to provide autonomous intelligent control actions in a distributed nature [5-8]. A Multi-agent system is capable of making intelligent decisions without human intervention, which is the key feature of this technology. Further, multi-agent system can provide flexible, extensible, and fault tolerance control and management systems. In recent literature [5-10], researchers have investigated applications of multi-agent system for operation of microgrids and other power distribution systems. Most of these multi-agent systems are only dealt with one or two smart grid functionalities and some of them are not implemented based on any industrial standards. As power engineering is a new application area of multi-agent system, it is necessary to make unique and feasible standards, tools, and design methodologies [11,12] for developing industrialized multi-agent systems in this field.

The objective of this research is to develop, and simulate a multi-agent system that enables an electricity market for the operation of a microgrid in both islanded and grid-connected modes. An autonomous intelligent multi-agent system has been implemented in JADE [13] platform, which is interfaced with Power World simulator [14] via an interfacing software EZJCOM [15]. The multi-agent system uses Power World simulator during the market based operation of the system to confirm the operation without any violation of technical constraints. The multi-agent system maximizes the power production of local distributed generators, and the power export to
the main distribution grid during grid-connected mode by providing a proper coordination between distributed energy resources. Simulation studies were carried out on the developed multi-agent system. The outcome of the simulation studies demonstrates the effectiveness of the proposed multi-agent system technique for market based microgrid operation.

The remaining paper is organized as follows: Section 2 briefly explains about microgrid, and its control and management. Section 3 formulates the problem mathematically. Section 4 proposes a multi-agent system for microgrid operation. Section 5 provides simulation studies, results, and discussion. Finally, the paper is concluded in section 6.

2. Microgrid Operation

Deregulated energy environment [16] has favoured a gradual transition from centralized power generation to Distributed Generation (DG) that allows the inclusion of energy sources at distribution network level. Distributed generation comprises several technologies such as diesel engines, micro turbines, fuel cells, wind turbines, and photovoltaic. Capacity of the distributed generators varies from few kilowatts to some megawatts.

![Figure 1. Network architecture of a typical microgrid.](image)

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. Common communication
structure and distributed control of distributed generators together with controllable loads and storage elements such as flywheels, capacitors, and batteries, are the main features of microgrids [2]. This innovative control and management architecture can be operated as interconnected to main distribution grid, or islanded from the main distributed grid. Network architecture of a typical microgrid is shown in Fig.1.

From the grid's point of view, microgrids can be regarded as controllable entities within the electrical power system that behave as aggregated loads, sources of power, and networks supporting ancillary services, depending on the abilities and status of the microgrids. From the customers’ point of view, microgrids are similar to traditional low voltage distribution networks that provide electricity to the customers. The operation of individual elements in the network can provide distinct benefits to the overall microgrid performance. Therefore, efficient control and management techniques should be developed with a proper coordination strategy between the elements.

2.1. Microgrid Control and Management

The main objective of microgrid control and management system is to optimize the operation of local power production output. Some of the functions handled by the microgrid management system are forecasting of electrical load and heat demand, forecasting of power production capabilities of renewable sources, generation scheduling, load shedding, emissions calculations, demand side management, and security assessment. Similar, microgrid control system has responsibilities such as ensuring micro sources that work properly at predefined operating points, satisfy operating limits and satisfy active and reactive powers necessity of the microgrid, disconnecting and reconnecting the main grid seamlessly, allowing market participation for micro sources and power exchanges with the utility, and providing black-start capabilities.

The microgrid control architecture [6,7,10] can be centralized or decentralized, which is normally decided by centralization roles assumed by the microgrid management system. In centralized control, local controllers follow the instructions of microgrid manager during grid-connected mode and have autonomy to perform their own controls during islanded mode. Centralized control is best suited for microgrids where, the owners of micro sources and loads have common goals and seek cooperation in order to meet their individual goals. In decentralized control, the main responsibility is given to local controllers that compete to maximize power production in order to satisfy the demand and provide maximum possible export to the main distribution grid. Decentralized control is best suited for microgrids in cases where micro-sources have different owners, in which case, several decisions should be taken locally; when microgrids operate in a market environment where, actions
of controllers of each unit should have a certain degree of intelligence; or where local micro-sources may have other tasks besides supplying power to the local distribution networks like producing heat for local installations, keeping the voltage at a certain level or providing a backup system for local critical loads in case of main system failure. In this research, a fully decentralized control scheme is proposed and implemented for the operation of a microgrid in a market environment that allows demand side management.

2.2. Microgrid Market

One of the key characteristic of a smart grid is enabling markets [16,17] for power system operation [1]. In this research, a microgrid market is proposed for microgrid operation where the microgrid participates in a power distribution market for exchanging power with the main distribution grid. A similar market is proposed in [18], where demand response is combined together with the market operation. Further, it is not highlighted clearly that constraints of the problem were handled in that paper. In this paper, according to the proposed market, the microgrid maximizes its profit by optimizing the power exchange with the main grid, and the customers are charged at market prices for their power consumption. The microgrid behaves as a single generator capable of relieving possible network congestion not only inside the microgrid but also on nearby feeders of the distribution network by exporting energy. During the islanded mode operation, the microgrid satisfies the local energy demand using its local power production and minimizes loss of load of the microgrid. The proposed market is beneficial for overall distribution network operation because the microgrid relieves possible network congestion by supplying its energy needs, on the other hand, network congestion as a result of peak demand leads to high electricity prices. Further, from the customer point of view, the microgrid minimizes operational cost and loss of load within the microgrid for market prices, and biddings of demand and distributed generators.

2.3. Demand Side Management (DSM) in Microgrid

Demand side management [19,20] plays an important role in smart grid operation, which affects the energy market. Demand side management can reduce the peak demand and reshape the load profile, which increases the grid sustainability by reducing the overall cost and carbon emission level. This will lead to the avoidance of the construction of an under-utilized electrical infrastructure in terms of generation capacity, transmission lines, and distribution networks. Smart pricing is a unique characteristic in smart grids made possible by the usage of smart metering devices in an automatic metering infrastructure. It could lead to cost-reflective pricing based on the entire supply chain of delivering electricity at a certain location, quantity, and period. When used in tandem
with the relevant demand side management techniques, control of the customer’s energy usage will be influenced by the real time penalty and incentive schemes at all levels of the supply chain. However, the motivation for the implementation of demand side management techniques within the context of the smart grid is to encourage the overall system efficiency, security and sustainability by making full utilization of the existing network infrastructure while facilitating the integration of low carbon technology into the electrical network. Demand side management can also play a significant role in electricity markets [16]. If the demand side management system informs the cluster’s central controller about the new load reschedule and the available load reduction capabilities for each time step of the next day, the central controller can then place bids in the market offering load reduction capacity during periods of peak demand. Profits made can then be reimbursed to customers of that cluster.

![Load shifting technique in demand side management.](image)

The designed demand side management system will benefit from smart grid communication infrastructure allowing a two way real time communication between the central controller and the controllable loads. The criteria for deciding the optimal load consumption can vary widely. The criteria could be to maximize the use of renewable energy resources, to maximize the economic benefit by offering bids to reduce demand during peak periods, to minimize the amount of power imported from the main grid and peak reduction. In this paper, demand side management agent runs a generalized load shifting technique that is illustrated in Fig.2. The objective of the proposed technique is to schedule the connection moment of each shiftable device within the system in a way that brings the total load consumption curve as close as possible to a given objective load consumption curve. The concern problem is formulated as minimization problem, which is solved by generic algorithm. In addition, the demand side management agent do load curtailment dynamically when it is necessary for the system operation.

3. Problem Formulation

A schematic diagram of a microgrid is shown in Fig.3, which would help to understand the problem formulation.
3.1 Day-Ahead Market

According to the proposed market, day-ahead planning of microgrid operation can be mathematically formulated as follows. The microgrid maximizes the corresponding revenues by exchanging power with the main grid. Consumers are charged for their power consumption at open market prices. Objective function of the microgrid at time $t$ is given by,

$$ \text{Maximize}\{\text{Profit}(t)\} = \text{Maximize}\{\text{Revenue}(t) - \text{Expenses}(t)\} $$  \hspace{1cm} (1)

According to the proposed policy, the microgrid sells power to internal load of the microgrid and also exchanges power with the main grid at market price. If the sum of power produced by microgrid sources is not enough, or too expensive to cover the local load, power $P_g(t)$ is bought from the upstream network and sold to the consumers at the same price. Corresponding revenue is given by below expression,

$$ \text{Revenue}(t) = C(t) P_g(t) + C(t) \sum_{i=1}^{N} P_i(t) $$ \hspace{1cm} (2)

Where, $C(t)$ is the open market price, $P_i(t)$ is the power production of the $i$th distributed generator, and $N$ is the number of the distributed generators that offer bids for power production. The expenses are the cost for power bought from the main grid. Corresponding expenses are given by below expression.

$$ \text{Expenses}(t) = \sum_{i=1}^{N} \text{bid}(P_i, t) + C(t) P_g(t) $$ \hspace{1cm} (3)

Where, $\text{bid}(P_i, t)$ is the bid from $i$th DG source at time $t$. Therefore, the profit of microgrid is given by,

$$ \text{Profit}(t) = C(t) \sum_{i=1}^{N} P_i(t) - \sum_{i=1}^{N} \text{bid}(P_i, t) $$ \hspace{1cm} (4)

According to the proposed market policy, at least internal demand of the microgrid should be met. Therefore, the above maximization problem is subjected to this system constraint, which can be written as,
\[ Pg(t) + \sum_{i=1}^{N} P_i(t) \geq P_I(t) \]  

Where, \( P_I(t) \) is the internal demand of the microgrid.

Further, the above maximization problem is subjected to the technical limits of each units also.

\[ P_u(t) = P_I(t) - P_f(t) \]  

where, \( P_u(t) \) is the renewable-battery power, and \( P_f(t) \) is net power from the distributed generators at time \( t \).

\[ P_{\text{Rew}}(t) - P_b(t) - P_u(t) = 0 \]  

\[ P_{\text{pv}}(t) = f(G_a(t), T_a(t)) \]  

\[ P_{\text{wind}}(t) = f(V_w(t)) \]  

\[ P_{\text{Rew}}(t) = P_{\text{pv}}(t) + P_{\text{wind}}(t) \]  

\[ P_u(t) < p_u^{\text{max}} \]  

\[ |P_b(t)| < p_b^{\text{max}} \]  

\[ C(t) = C(t-1) + \left[ \frac{\Delta t \eta_b(t)}{V_b(t)}(P_{\text{Rew}}(t) - P_u(t)) \right] \]  

\[ C(t)|_{t=0} = C_s \]  

\[ C(t)|_{t=N_t} = C_f \]  

\[ C_{\text{min}} < C(t) < C_{\text{n}} \]  

where, \( C(t) \) and \( C(t-1) \) represent battery charges at time \( t \) and \( t-1 \) respectively, \( \eta_b(t) \) is battery efficiency at time \( t \), \( V_b(t) \) is voltage at battery terminals at time \( t \), \( P_{\text{Rew}}(t) \) is total renewable power at time \( t \), \( P_{\text{pv}}(t) \) is total photovoltaic power at time \( t \), \( G_a(t) \) is total insolation on PV at time \( t \), \( T_a(t) \) is ambient temperature at PV at time \( t \), \( P_{\text{wind}}(t) \) is the total wind power at time \( t \), \( V_w(t) \) is wind speed at wind plant at time \( t \), \( P_b(t) \) is battery power at time \( t \), \( P_u^{\text{max}} \) is maximum renewable penetration to the system, \( P_b^{\text{max}} \) is maximum battery power, \( C_{\text{max}} \) is maximum battery charge, and \( C_{\text{min}} \) is minimum battery charge.

In addition, this maximization problem is subject to constraints [12] of distributed generators such us fuel limits, generation limits, and rump up and ramp down limits.

### 3.2 Demand Side Management

The proposed demand side management technique schedules the connection moments of each shiftable device within the system in a way that brings the total load consumption curve as close as possible to the objective load
consumption curve. The problem can be formulated as a minimization problem that can be expressed mathematically as follows.

Minimize,

\[ \sum_{t=1}^{N} (P_{load}(t) - \text{Objective}(t))^2 \]  

where, \( \text{Objective}(t) \) is the value of the objective curve at time \( t \), and \( P_{load}(t) \) is the actual consumption at time \( t \), which is given by,

\[ P_{load}(t) = \text{Forecast}(t) + \text{Connected}(t) - \text{Disconnected}(t) \]  

where, \( \text{Forecast}(t) \) is the forecasted consumption at time \( t \), and \( \text{Connected}(t) \) and \( \text{Disconnected}(t) \) is the amount of loads connected and disconnected at time \( t \) respectively during the load shifting.

The term \( \text{Connected}(t) \) is made up of two parts: The increment in the load at time \( t \) due to the connection times of devices shifted to time \( t \), and the increment in the load at time \( t \) due to the device connections scheduled for times that precede \( t \). \( \text{Connected}(t) \) is given by the following equation,

\[ \text{Connected}(t) = \sum_{i=1}^{t-1} \sum_{k=1}^{D} X_{kit} P_{tk} + \sum_{l=1}^{j-1} \sum_{i=1}^{t-1} \sum_{k=1}^{D} X_{ki(t-1)} P_{(1+l)k} \]  

where, \( X_{kit} \) is the number of devices of type \( k \) that are shifted from time step \( i \) to \( t \), \( D \) is the number of device types, \( P_{tk} \) and \( P_{(1+l)k} \) is the power consumed at time steps 1 and \( 1 + l \) respectively for device type \( k \), and \( j \) is the total duration of consumption for device of type \( k \).

Similarly, the term \( \text{Disconnected}(t) \) also consists of two parts: The decrement in the load due to delay in connection times of devices that were originally supposed to begin their consumption at time step \( t \), and the decrement in the load due to delay in connection times of devices that were expected to start their consumption at time steps that precede \( t \). \( \text{Disconnected}(t) \) is given by the following equation,

\[ \text{Disconnected}(t) = \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{ktq} P_{tk} + \sum_{l=1}^{j-1} \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{k(t-1)q} P_{(1+l)k} \]  

where, \( X_{ktq} \) is the number of devices of type \( k \) that are delayed from time step \( t \) to \( q \), \( m \) is the maximum allowable delay.

This minimization problem is subject to the following constraints,

The number of devices shifted cannot be a negative value.

\[ X_{kit} > 0 \quad \forall i, j, k \]
The number of devices shifted away from a time step cannot be more than the number of devices available for control at the time step.

\[
\sum_{t=1}^{T} X_{kit} \leq Ctrlk(i)
\]

(22)

where, \( Ctrlk(i) \) is the number of devices of type \( k \) available for control at time step \( i \).

4. Proposed Multi-Agent System for Microgrid Operation

Multi-agent system [4] is a powerful tool for solving complex problems in a decentralized manner. Multi-agent system is a well suited technology for solving problems that require interactions between a large number of distinct entities, add and extend functionalities continuously over time, have enough data and information available locally to undertake a decision without the need for communication with a central point, and require to implement new functions and elements within the existing plant items and control systems. In context of power distribution systems, multi-agent technologies can be applied in a variety of applications such as market based operation, demand side management, disturbance and fault diagnosis, voltage control, system restoration, and system monitoring and visualization.

The market based microgrid operation can be simulated by a multi-agent system having a group of geographically distributed, autonomous, and adaptive intelligent agents. Each agent has only a local view of the system. With certain kinds of coordination, a team of agents can perform wide area control schemes. The coordination is necessary to avoid conflicts among decisions and actions from the agents.

4.1. Proposed Multi-Agent System

A distributed multi-agent system architecture is proposed for market based operation of a microgrid. The multi-agent system was implemented in JADE platform, which is interfaced with Power World simulator. The multi-agent system uses Power World simulator to confirm that there is no technical violation during the microgrid operation. The proposed architecture is shown in Fig.4. Generic architecture of the proposed intelligent agent [21] in the multi-agent system is shown in Fig.5. Each agent executes a set of behaviours that are set by the designer based on the agent's goal, functions, and roles.

The multi-agent system is implemented according to IEEE FIPA [22] standards. JADE is a FIPA compliant multi-agent platform, which supports a certain style of agent implementation. A layered architecture is
employed for designing of intelligent agents in JADE that allows three basic layers namely message handling layer, behavioural layer, and functional layer.

Figure 4. Schematic diagram of MAS - Microgrid.

Figure 5. Generic architecture of an intelligent agent.

Figure 6. Layered architecture of an intelligent agent [13].
The functional layer embodies the core functional attributes of the agent, the behavioural layer provides control of an agent when specific tasks are carried out, and the message handling layer is responsible for the sending and receiving of messages from other agents, and implementing the relevant Agent Communication Language (ACL) and ontology. The three layered agent architecture is shown in Fig.6.

4.2. Agents in the Multi-Agent System

The developed multi-agent system consists of several distributed generator agents (DG Agent), load (Load Agent) agents, a renewable energy source agent (RES Agent), a storage system agent (Storage Agent), a microgrid manager agent (MGM Agent), a schedule coordinator agent (SC Agent), a database agent (Database Agent) and other administrative agents. A brief description of the main agents that incorporate in the multi-agent system are given below.

**MGM Agent:** This is main agent responsible for controlling and managing the microgrid. Monitoring, scheduling, and managing distributed energy resources, and performing demand side management are some of the main functions of this agent. MGM Agent activates SC Agent in response to balance supply and demand for a period.

**SC Agent:** SC Agent is activated by MGM Agent when generation scheduling is necessary for a period. This agent negotiates with DG Agents and Load agents to decide economic schedule for the period.

**DSM Agent:** This is responsible for demand side management of the system. In this project, this agent runs load shifting technique optimized by genetic algorithm in a day advance, and do load curtailment dynamically when it is necessary.

**Database Agent:** This keeps data and information of all available agents and their tracks and capabilities.

**DG Agent:** This is responsible for monitoring, controlling and negotiating its power level and status. This agent has fixed data such as unit name, minimum and maximum power levels, fuel cost coefficients, and variable data such as power setting and status.

**RES Agent:** This is responsible for monitoring, controlling and negotiating its power level. This agent is interfaced with database agent to get meteorological data for calculating forecasted renewable power output. The renewable sources are mathematically modelled as in [23].

**Load Agent:** This is capable of monitoring, controlling and negotiating power level of load and its status. It has flexibility to implement demand side management techniques.
Storage Agent: This manages the storage elements in the microgrid and provides the best schedule of storage elements such as fuel stack, electrolyzer, and battery banks to provide optimum energy density and power density. This agent monitors state of charge (SOC) level of storage system and respond based on current SOC as well as requests from MGM Agent.

PWS Agent: It represents microgrid network in Power World simulator into the multi-agent system.

4.3. Coordination between Agents

According to the proposed market policy, Distribution Management System (DMS) that contains Distribution Network Operator (DNO), and Market Operator (MO) handles the market operation of the microgrid [24]. DNO and MO behave in a similar manner to ISO and PX respectively in the deregulated power system. In the day-ahead hourly market, distributed generators bid 24-hourly supply quantities at various prices, loads bid 24-hourly demands at various prices. The corresponding Market Clearing Prices (MCP) and Market Clearing Quantities (MCQ) are determined for each hour. The MO handle this procedure and schedules supply and demand, and the DNO finalizes the schedules without any congestion and technical violation with the help of Power World simulator.

In this simulation platform, intelligent agents represent individual autonomous entities and interact with other agents pro-actively. Interaction of agents and respective messages for a day-ahead scheduling are shown in Fig.7. Proposed algorithms for generation scheduling of the microgrid in grid-connected and islanded modes are given in Fig.8 and Fig.9 respectively.
PV Power

Wind Power

DG Power for Current Market Price

Total Internal Power = DG Power + Rew. Power

Sell Power to Grid = Total Internal Power - Load Power

Start

Rew. Power = PV Power + Wind Power

Total Internal Power > Load Power

Yes

Power Needed = Load Power - Total Internal Power

No

Power Needed > Max. Limit of Grid Power

Yes

Available Power = Total Internal Power - Load Power

No

Power Needed = Load Power - Total Internal Power

Grid Power = Max. Limit of Grid Power

Power Needed = Load Power - (Total Internal Power + Grid Power)

Yes

Battery Power = Allowable Battery Power

No

Battery Power = Power Needed

Yes

Battery Power = Power Needed - Battery Power

End

Battery Power = Available Power

No

Battery Power = Allowable Battery Power

End

Available Power = Total Internal Power - Load Power

Allowable Battery Power > Available Power

Battery Power = - Available Power

No

Battery Power = - Allowable Battery Power

End

Power Needed = Load Power - Total Internal Power

Battery Power = Allowable Battery Power;

Power Needed = Power Needed - Battery Power

Yes

Power Needed > 0

End

No

Power Needed = Power Needed

End

Load Curtailment = Power Needed

Figure 8. Proposed algorithm behind the interaction of agents in grid-connected mode.

Figure 9. Proposed algorithm behind the interaction of agents in islanded mode.
5. Simulation Studies

Simulations were carried out on the developed multi-agent system for microgrid, which serves a primarily industrial customers over a 24-hour period. The electrical network of the microgrid is shown in Fig. 10.

![Electrical network diagram of the microgrid](image)

Figure 10. Electrical network diagram of the microgrid.

The entire network operates at 410V. Each interconnection link including the link between the microgrid and the main grid has a resistance of 0.003pu, a reactance of 0.01pu, a length of 10km, and maximum power transfer limit of 750kVA.

<table>
<thead>
<tr>
<th>Bus</th>
<th>DER</th>
<th>Load (%)</th>
<th>Minimum Power (kW)</th>
<th>Maximum Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diesel Generator 1 (Diesel)</td>
<td>10.0</td>
<td>50</td>
<td>350</td>
</tr>
<tr>
<td>2</td>
<td>Diesel Generator 2 (Bio-diesel)</td>
<td>7.5</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>Wind Turbine</td>
<td>12.5</td>
<td>0</td>
<td>280</td>
</tr>
<tr>
<td>4</td>
<td>Photovoltaic</td>
<td>15.0</td>
<td>0</td>
<td>864</td>
</tr>
<tr>
<td></td>
<td>CESS</td>
<td></td>
<td>0</td>
<td>1000 &amp; 5000kWh</td>
</tr>
<tr>
<td>5</td>
<td>Fuel Cell</td>
<td>20.0</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>6</td>
<td>Micro Turbine (Natural Gas)</td>
<td>35.0</td>
<td>180</td>
<td>720</td>
</tr>
</tbody>
</table>
The microgrid consists of a PV system, a wind plant, several other types of distributed generators and a battery bank. It is assumed that the renewable sources are connected through Maximum Power Point Tracking (MPPT) controllers. The details about the distributed energy resources in the microgrid and their placements in the system are given in Table 1 and Table 2. All distributed generators produce power at unity power factor, and power factor of each load is unity. This means neither requesting nor producing reactive power in the system.

Table 2. Details of distributed generators

<table>
<thead>
<tr>
<th>DG</th>
<th>Maximum Power (kW)</th>
<th>Minimum Power (kW)</th>
<th>Operating cost ((a + bP + cP^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
</tr>
<tr>
<td>FC</td>
<td>10</td>
<td>5</td>
<td>0.38 0.0267 0.00024</td>
</tr>
<tr>
<td>Micro Turbine</td>
<td>20</td>
<td>5</td>
<td>0.40 0.0185 0.00042</td>
</tr>
<tr>
<td>Diesel Generator 1</td>
<td>70</td>
<td>10</td>
<td>0.65 0.0152 0.00052</td>
</tr>
<tr>
<td>Diesel Generator 2</td>
<td>30</td>
<td>10</td>
<td>0.45 0.0166 0.00021</td>
</tr>
</tbody>
</table>

The simulation was carried out for a typical day. Wholesale energy price and hourly load demand of the microgrid for the day are given in Fig.11 and Fig.12 respectively.

Table 3 contains normalized data of wind power and PV power production, which have been calculated from the models proposed in [23]. Normalized power production of a renewable source is the ratio of power output from the source to the power rating of the source. Perfect forecasting of wind speed, solar radiation, atmospheric temperature, and load are taken from the meteorological department [25].
Table 3. Normalized RES production on the day

<table>
<thead>
<tr>
<th>Hr</th>
<th>Wind</th>
<th>PV</th>
<th>Hr</th>
<th>Wind</th>
<th>PV</th>
<th>Hr</th>
<th>Wind</th>
<th>PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0860</td>
<td>0</td>
<td>9</td>
<td>0.4450</td>
<td>0.6358</td>
<td>17</td>
<td>0</td>
<td>0.2546</td>
</tr>
<tr>
<td>2</td>
<td>0.1465</td>
<td>0</td>
<td>10</td>
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<td>0.6780</td>
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5.1. Simulation Results

The simulation studies were carried out on the proposed multi-agent system that facilitates the electricity market based operation of the microgrid in both islanded and interconnected modes. There are over 100 controllable loads from 6 types of devices available for demand side management in the microgrid. The resultant load demand obtained from the DSM Agent is given in Fig.13. The system achieved a profit of 10% by the demand side management. Once the demand side management agent has calculated the load demand for the scheduling, the SC Agent continues the coordination between the agents for generation scheduling as proposed in Fig.7.

![Figure 13. Hourly load profile of after demand side management.](image)

Fig.14 shows the power settings of energy sources during the grid-connected mode operation of the microgrid. As can be seen, during the grid-connected mode, microgrid sell or buy the power from the main grid. From 4hrs to 9hrs and from 12hrs to 16hrs, microgrid buys the power from the grid, and it sells power to the grid in the rest of the day.
Generally, a significant part of power generation for microgrids is expected to come from renewable energy resources. The unpredictability of the renewable sources makes the islanded operation and dispatch of microgrids challenging. In this situation the load control is very desirable and in some cases a real necessity. A common way to safely operate a small isolated microgrid, where renewable power generation is significant, is to provide some storage, which stores energy when there is excess energy in the system and provides power when power is needed in the system.

Fig.15 shows the power settings of energy sources during the islanded mode operation of the microgrid. As can be seen from the figure, storage system is at charging state from 4hrs to 9hrs, and from 12hrs to 16hrs, and it discharges power in the rest of the day. This charging and discharging periods are the same as the buying and
selling power to and from the main grid in grid-connected mode. This happened because there is enough storage capacity in the microgrid to store and discharge energy whenever it is necessary. The microgrid considered in the simulation studies contains 1000kW, 5000kWh storage system. This is enough to store excess energy when there is excess energy and provides required power for satisfying the whole microgrid load, expect at one place. At 20th hr, the battery power is reached its maximum power. As a result, some load curtailment is done by DSM Agent at the time.

![Figure 16. Power settings of DER in islanded mode of the microgrid with 500kW storage system.](image)

Most of microgrid designers limit storage system is around 30% of microgrid peak load by several reasons like high capital cost. A simulation was carried out on the same microgrid with only 500kW, 2500kWh storage system. Fig.16 shows the power settings of distributed energy resources during the operation of the microgrid in islanded mode. The results show that the storage system does not have sufficient capacity to supply the load with out performing dynamic load curtailment by DSM Agent. From 18hrs to 22hrs, the sources and storage system in the microgrid are not able to supply the whole demand. The unsatisfied demands are shown as load curtailments of those hours. From 4hrs to 7hrs, even though DG Agents can provide more power economically based on the market prices, DG Agents limit their power production only to satisfy the microgrid demand and storage system. This phenomenon can be seen by comparing DG output for same market prices either in Fig.14 or Fig.15.

5.2. Discussion

In this project, some of the smart grid characteristics were demonstrated clearly with the microgrid operation. In particular, a market based operation of a microgrid in a cooperative environment was modeled with multi-agent
system and simulation studies were carried out on the system in both islanded and interconnected modes of operations. Interaction among distributed energy resources in microgrid, and interaction between microgrid and the main grid are the crucial tasks for better development of design and control schemes for microgrids. This research proved that multi-agent system is one of the best promising approach to handle the interaction among the elements and also shows that microgrids at the distribution level provides more reliable supply to the customers.

Generally, microgrids could contain different types of customers and energy sources, and they can be operated with different sets of rules and policies. The authors presented multi-agent systems for scheduling of islanded microgrids with different polices [7,26]. They presented a cooperative multi-agent system in [26], where, a schedule coordinator agent schedules the resources by negotiating with each agent one by one according to a priority list without collecting data of all resources together at one place. The data of each resources is kept at resource level and a priority list is set such that minimizing the total operational cost the system. This methodology is better in deregulated market environment, where it is difficult to collect all information from all parties because of the commercial secrets. In contrast, a competitive multi-agent system [7] was presented for a microgrid operation in competitive environment by introducing PoolCo energy market, where every autonomous decision making entities were modelled as intelligent agents. During the operation, buyers (i.e. loads) submit their bids to the pool in order to buy power from the pool, and sellers (i.e. generators) submit their bids to the pool in order to sell power to the pool. According to the biddings of loads and generators, the PoolCo takes scheduling decision. Both multi-agent systems provided promising results in market based operation of microgrids in different types of energy environments.

6. Conclusion

Smart grid is defined by some key characteristics such as consumer friendliness, self-healing, attack resistant, ability to accommodate all types of generation and storage options, enabling markets, high power quality, optimizing assets, and operating efficiently. In this project, some of the characteristics were implemented and demonstrated through the operation of microgrid on multi-agent system platform. Further, this paper provides clear view of development, and simulation of a multi-agent system and proposes intelligent algorithms for the operation of distributed energy resources in an electricity market. Simulation studies were carried out on the developed system and the outcome of simulation studies demonstrates the effectiveness of the proposed multi-agent system for market based operation of a microgrid, and also shows the possibility of autonomous built-in
simulation of microgrids. As the developed multi-agent system is scalable, extendable, and easily reconfigurable, the developed system could be expanded for further studies.

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References


