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Multi Agent System for Distributed Management of Microgrids

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Abstract—In market operations, Distributed Generators (DGs) and price-sensitive loads participate in a microgrid energy market implemented in JADE. Each DG and each price-sensitive load is represented by the respective agents which perform various functions such as scheduling, coordination and market clearing subject to system, DG and load constraints. Each agent is assigned to one of the several agent objectives which maximizes either DG or load surpluses or both. In simulated operation of a microgrid, hourly power reference signals and load control signals from JADE are passed to DG and load models developed in MATLAB/Simulink using MACSimJX. Simulated operation of DGs and loads are studied by performing simulations under different agent objectives. Results from simulation studies demonstrate the effectiveness of implementing multi agent system (MAS) in the distributed management of microgrids.

Index Terms—Distributed generation, microgrid, multi agent system, deregulated energy market, JADE, MACSimJX.

I. INTRODUCTION

The general trend of distributed generator (DG) installations at distribution voltage level coupled with advances in communication and control, increased environmental awareness and escalating fuel prices have generated a significant interest in the research of microgrids [1]. High penetration of DG technologies such as diesel engines, combined cooling heat and power generating units (CCHPs), microturbines (MTs), photovoltaics (PVs), wind turbines (WTs) and fuel cells have transformed regulated power generation into restructured entities [2]. As a result, integration of DGs has become an important aspect for successful operation of microgrids among other operational and technical challenges faced [3, 4].

The concept of microgrids [5, 6] basically involves DGs, renewable energy sources, clusters of controllable loads and

energy storage systems (ESSs) operating in a coordinated manner to supply reliable electricity and reduce energy prices. In addition, microgrids are expected to improve power quality, reduce transmission losses, provide system reliability and enable integration of DGs and renewable sources [7]. An IEEE standard [8] was also established which provides a set of guidelines for interconnection of distributed energy resources (DERs). Furthermore, microgrids have the capability to operate in either grid connected or islanded mode. In grid connected mode, microgrids aim at satisfying demand through local generation. Excess or deficit power in a microgrid can be absorbed or supplied by the grid respectively. In islanded mode, power balance within the microgrid must be observed between generation and demand in order to maintain system frequency and stability.

Market operations and distribution networks become increasingly complex as the power industry moves towards decentralization [9]. The presence of DERs at distribution voltage level will inevitably change the way power flows within the network causing it to change from a passive to an active one. Consequently, centralized supervisory control and data acquisition (SCADA) which was originally designed for traditional passive networks may be inadequate to cope with the high penetration of DERs and complex control decisions due to the lack of flexibility and extensibility [10]. Moreover, assumptions applied to conventional power systems may not be valid for active distributed systems which raise challenges in the operation of microgrids [11].

Main issues regarding integration of DERs are also highlighted in [12-14] which primarily include 1) the need for scheduling and dispatch of DGs under supply and demand uncertainties, 2) design of new market models that enables competitive participation within a microgrid, 3) development of market and control mechanisms which exhibits plug-and-play for seamless integration of DERs, 4) cooperation and control which are distributed and realized with minimal information exchange with the central controller and finally, 5) communication networks which are based on standard components such as TCP/IP protocol. Most of these issues can be addressed by providing an agent platform with a common communication interface in the distributed system [15].

MAS has been widely proposed as a feasible approach for managing complex distributed systems [16]. The extension of MAS into microgrid applications is also evident in [17-19] where various research activities ranging from agent based

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market operation, fault protection schemes and distributed energy management systems to real time implementations. In addition, proposed guidelines and requirements on the use and applications of MAS in power systems are discussed in detail [20, 21]. Key motivation for proposing MAS in power systems basically lies in its inherent benefits such as flexibility, scalability, autonomy and reduction in problem complexity among other factors.

In [22], MAS was used to simulate multiple microgrid market scenario involving load and generation agents with and without storage systems. MAS was also implemented in energy market simulation using risk-based continuous double auction algorithm [23]. In [24], MAS was applied to microgrids to participate in ancillary service markets. The proposed auction algorithm which solves asymmetric assignment problems is discussed in [25]. In [17], MAS implementation for operation of a microgrid is presented. The MAS design and implementation of microgrids for seamless transition from grid-connected to islanded mode in MATLAB/Simulink environment is discussed in [19].

Although many microgrid research activities involving MAS have been reported, no proper MAS platform was implemented via integration of microgrid market operations and DERs. The work reported in the literature specifically focuses on either intelligent market operations or DER implementations while coordinated actions between market operations and DER implementations in microgrids are seldom addressed. This paper addresses this issue by proposing a multi agent based system which integrates microgrid market operations and implementation of DERs using Simulink, Java agent development framework (JADE) [26] and multi agent control simulation Jade extension (MACSimJX) [27]. The key intention of this paper is to coordinate agent-based market activities with DER implementations which are separately addressed in the literature. In addition, the developed multi agent system acts in accordance to the foundation for intelligent physical agents (FIPA) [28] specifications which provide standards for agent development and implementation. The proposed multi agent based system models a market scenario where each energy seller or each energy buyer is represented by an agent that aims to maximize the benefits according to the defined agent objectives while ensuring the smooth operation and proper execution of microgrid operations under the simulated real-time environment. Two functions of microgrid operations were also demonstrated which include price-driven generation and demand scheduling and locational marginal pricing (LMP) [29-31] for various participants in a distributed microgrid energy market.

The remaining paper is organized as follows. Section II discusses the types of microgrid control architecture. Section III formulates the problem mathematically. Section IV describes the proposed multi agent based system. Section V provides simulation studies and result analysis. Section VI provides conclusions for the paper.

II. MICROGRID CONTROL ARCHITECTURE

Control architecture of a power system can be broadly classified into two distinctive categories which are centralized and decentralized controls. The main difference between the two types of control lies in the management of tasks and responsibilities given to the respective controllers. In a dynamic microgrid where DGs and loads typically have different ownerships, variations in generation and demand raise challenges in forecasting. They result in high levels of uncertainties. In addition, information on power quantity and cost function of DGs and loads is also not readily known [11]. Therefore, appropriate control schemes and coordination strategies are necessary for efficient microgrid operations.

A. Centralized Control

A fully centralized control usually consists of a dedicated central controller which executes a range of functions such as gathering data, performing calculation and optimization and determining control actions for all units. In addition, all of these functions are done at a single point which requires an extensive communication infrastructure for the central controller and controlled units to interact.

However, due to the need for processing large amounts of information at a single point simultaneously, centralized control is unable to exhibit plug-and-play feature which is required in a microgrid setup. Consequently, this restricts power system expansion and poses limitations on planning of power systems among other factors [32]. Generally, centralized control is more suited for standalone power systems which need to maintain critical supply and demand balances in a slow changing infrastructure.

B. Hierarchical Control

A fully decentralized control typically consists of many local controllers where each controller controls a single unit. These controllers only gather local information about the unit under control and is neither fully aware of system level parameters nor control actions from neighboring controllers [33]. However, in a system where the presence of strong coupling between various operating units requires a minimum level of coordination, a fully decentralized control is unable to achieve stable operation based on local information alone. As a result, a hybrid form of control known as hierarchical control

Fig. 1. Schematic diagram of hierarchically controlled microgrid

is proposed in Fig. 1 for the microgrid due to the presence of numerous controllable devices and stringent performance requirements [34, 35]. In general, decentralized control is applicable for grid-connected microgrids comprising many fast changing DGs with different ownerships.

The proposed MAS framework in this paper basically consists of a group of intelligent agents interacting with each other to achieve local and global objectives. Each agent has limited knowledge of the environment and is provided a set of allocated tasks and responsibilities in order to achieve its goals through information exchanges with other agents [36]. Agents also exhibit other key attributes which include sociability, reactivity, pro-activeness, reliability and mobility [20]. These attributes coupled with the autonomy given to agents make MAS a suitable alternative for coordinated microgrid operation in a competitive market environment with numerous DG owners [17].

III. PROBLEM FORMULATION

As mentioned previously, MAS is proposed for generation and demand scheduling and the LMP for various participants in the distributed microgrid energy market. Generator and load agents retrieve power scheduling information based on their incremental cost slope and price signals obtained from the proposed microgrid energy market. The power reference and load control signals are then sent to the generator and load correspondingly. The price signal refers to the Market Clearing Price (MCP) which is derived from the submitted bids of generator and load. Subsequently, the derived MCP establishes the price reference in LMP among other variables where the participants will pay or be paid at that price. The amount that each generator or load agent receives or pays respectively depends on some objectives imposed on the agents.

A. Market Clearing Price and Scheduling Problem

The idea of proposing a microgrid market structure is to encourage a competitive electricity market since DERs are considered more economical to generate energy locally at least for a certain peak period compared to buying directly from the main grid [37]. In addition, a real-time market clearing technique is used to determine the MCP. The objective in determining MCP is to dispatch an aggregate of different types of DGs to an aggregate of different consumers. A double-sided bidding mechanism is considered. All bids to sell energy will be priced at the marginal cost of the energy.

Consider the power generated by the i^{th} generation bidder where the supply curve is approximated based on the fuel consumption data. It is expressed as:

$$p_{G,i} = \frac{c_{G,i}}{m_{G,i}} \quad (1)$$

where $p_{G,i}$ is the active power of the i^{th} generator; $c_{G,i}$ is the price for generating $p_{G,i}$; and $m_{G,i}$ is the gradient of the i^{th} supply curve and is commonly referred to as the bidding rate of the i^{th} generator in the subsequent sections.

Likewise, consider the load required by the j^{th} demand bidder where the demand curve is expressed as:

$$p_{D,j} = \frac{c_{oD,j}}{m_{D,j}} - \frac{c_{D,j}}{m_{D,j}} \quad (2)$$

where $p_{D,j}$ is the active demand required by the j^{th} demand bidder; $c_{oD,j}$ is the price intercept of the j^{th} demand curve; $c_{D,j}$ is the price offered by the j^{th} load to consume $p_{D,j}$; and $m_{D,j}$ is the bidding rate of the j^{th} demand bidder.

In a balanced system where the total generation equals the total load demand, MCP can be determined [38] as expressed:

$$MCP = \frac{\sum_{j=1}^M \frac{c_{oD,j}}{m_{D,j}}}{\sum_{i=1}^N \frac{1}{m_{G,i}} + \sum_{j=1}^M \frac{1}{m_{D,j}}} \quad (3)$$

where N is the number of generators; and M is the number of loads participating in the competitive market.

The dispatch for generators and loads can be determined by substituting the value of MCP obtained from (3) into (1) and (2) respectively subject to the following constraints.

The total microgrid generation and load must be balanced at all times with the utility grid either injecting or absorbing energy during unbalanced periods.

$$\sum_{i=1}^N p_{G,i} + p_{Grid} = \sum_{j=1}^M p_{D,j} \quad (4)$$

where p_{Grid} is the active power delivered from/to the utility grid to maintain power balance within the microgrid.

Each generation unit has to abide by generation limits.

$$p_{G,i}^{\min} \leq p_{G,i} \leq p_{G,i}^{\max} \quad (5)$$

where $p_{G,i}^{\min}$ is the minimum power generated by the i^{th} generation; and $p_{G,i}^{\max}$ is the maximum power generated by the i^{th} generation.

Similarly, each load has a consumption limit to follow.

$$p_{D,j}^{\min} \leq p_{D,j} \leq p_{D,j}^{\max} \quad (6)$$

where $p_{D,j}^{\min}$ is the minimum power required by the j^{th} load which is also regarded as critical load; and $p_{D,j}^{\max}$ is the maximum power required by the j^{th} load based on the maximum capacity rating.

In addition, whenever the utility grid is required to maintain power balance in the microgrid due to either insufficient or excess generation, market participants will follow utility grid prices accordingly during market clearing.

B. Locational Marginal Pricing

The nodal pricing or LMP refers to the lagrangian multipliers which are derived from active power flow equations at each bus within a system [29]. LMP was selected as the pricing mechanism because it takes into account power losses among other factors which are typical in a medium-low voltage network. Basically, LMP at any node in the system consists of three components which include reference marginal cost, a marginal loss component and a congestion component expressed as:

$$\text{LMP} = \lambda_{ref} + \frac{\partial P_{loss}}{\partial P_i} \lambda_{ref} + \lambda_{congestion} \quad (7)$$

where λ_{ref} is the reference marginal cost which is obtained from (3) and is the same for all nodes in the system; $(\partial P_{loss}/\partial P_i) \lambda_{ref}$ is the marginal loss component which is further explained in the subsequent section and $\lambda_{congestion}$ is the congestion component which generally consists of a shadow price and a generation shift factor.

Therefore, the LMP for each market participant will be location specific factoring into account marginal losses component. In subsequent sections, the congestion component will not be considered as no congestion is assumed in the illustrated system i.e. $\lambda_{congestion}$ equals zero.

C. Marginal Loss Factor

The loss sensitivity factor, $\partial P_{loss}/\partial P_i$ is part of the marginal loss component in (7) and is referred as incremental loss [39]. Loss sensitivity factors in a power system are derived directly from AC power flow. The first step determines the ratio of change in power at the reference bus, ΔP_{ref} when a change in power at bus i , ΔP_i or ΔQ_i is made. It can be written for N buses in the network and is expressed as:

$$\begin{bmatrix} \frac{\partial P_{ref}}{\partial P_1} \\ \frac{\partial P_{ref}}{\partial Q_1} \\ \vdots \\ \frac{\partial P_{ref}}{\partial P_N} \\ \frac{\partial P_{ref}}{\partial Q_N} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{ref}}{\partial \theta_1} \\ \frac{\partial P_{ref}}{\partial |E|_1} \\ \vdots \\ \frac{\partial P_{ref}}{\partial \theta_N} \\ \frac{\partial P_{ref}}{\partial |E|_N} \end{bmatrix} \quad (8)$$

where J^T is the transpose of the inverse Jacobian matrix for the network. The phase angles and voltage magnitudes in the network can then be obtained by employing any non-linear programming techniques available. An Interior Point Method (IPM) [40] is used in this paper for determining changes in phase angle and voltage magnitude parameters in the network.

Next, evaluate the loss sensitivity factor which is the ratio of change in real system losses when a change in power at bus i , ΔP_i is made. Likewise, it can be extended to N buses and is expressed as:

$$\begin{bmatrix} \frac{\partial P_{loss}}{\partial P_1} \\ \vdots \\ \frac{\partial P_{loss}}{\partial P_N} \end{bmatrix} = \begin{bmatrix} \frac{\partial \theta_1}{\partial P_1} & \dots & \frac{\partial \theta_N}{\partial P_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \theta_1}{\partial P_N} & \dots & \frac{\partial \theta_N}{\partial P_N} \end{bmatrix} \begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta_1} \\ \vdots \\ \frac{\partial P_{loss}}{\partial \theta_N} \end{bmatrix} \quad (9)$$

where $(\partial \theta_i/\partial P_j)$ are the values obtained from (8) for every i and j and $(\partial P_{loss}/\partial \theta_j)$ are obtained by taking the derivatives of P_{loss} with respect to θ_j . Therefore, the incremental loss at each bus in the network is obtained and will be subsequently used by LMP to compute the nodal price at each node in the network.

D. Agent Optimization Objectives

The generation and load agents developed in this paper are given certain objectives to accomplish. There are basically three different objectives available where each objective specifies a different policy of market operation.

The first objective that agents may be tasked to perform is to maximize DG surplus. Agents tasked with this objective aim at maximizing the profit of generation agents which participate in the trading process. Generation agents can either sell their energy to load agents or the utility grid depending on MCP derived in (3) or the grid buyback price. The profit for each generation agent is expressed as:

Profit_{Gi} = Revenue - Generation cost

$$= [c_{BB,Grid} P_{Gi,exchange} + P_{Gi,\mu grid} \text{LMP}] - [0.5 P_{Gi,sch} \lambda_{ref}] \quad (10)$$

where $c_{BB,Grid}$ is the grid buyback price for the power injected back into the utility grid; $P_{Gi,exchange}$ is the power flow exchange between the utility grid and the i^{th} DG; $P_{Gi,\mu grid}$ is the power sold to the microgrid load; and $P_{Gi,sch}$ is the total scheduled power sold to the microgrid load and the utility grid.

Similarly, the second objective is to maximize load surplus. Agents under this objective aim at maximizing savings for the load which also implies minimizing the load cost for each load agent. Load agents can either buy energy from the generation agent or directly from the utility grid depending on energy prices during trading. The load saving for each load agent can be expressed as:

Save_{Dj} = Load cost - Amount payable

$$= 0.5 P_{Dj,sch} (\lambda_{ref} + c_{oD,j}) - [c_{RP,grid} P_{Dj,grid} + P_{Dj,\mu grid} \text{LMP}] \quad (11)$$

where $P_{Dj,sch}$ is the total scheduled power bought from generation agents and the utility grid by the j^{th} load agent; $c_{RP,grid}$ is the retail price offered by the utility grid; $P_{Dj,grid}$ is the amount of power bought from the utility grid; and $P_{Dj,\mu grid}$ is the amount of the power bought from generation agents.

Consequently, the third objective is to maximize both DG and load surplus simultaneously which is the combination of (10) and (11). In (10), the maximization of DG surplus focuses mainly on the generation agents such that it also maximizes load costs at the same time. Similarly, (11) focuses mainly on load agents such that it minimizes DG profits at the same time. Therefore, the third objective aims at maximizing generation and load agent surplus simultaneously.

IV. PROPOSED MULTIAGENT PLATFORM

The proposed MAS approach for simulating market environment as well as simulated response of DERs is shown in Fig. 2. The developed multi agent and coordination system operate in compliance with IEEE FIPA specifications [28]. Market and control operations were implemented in JADE and the coordination layer between Simulink models and agents were implemented in MACSimJX which uses TCP/IP protocol and windows pipe for its communication channels.

Fig. 2. Schematic diagram of proposed multiagent system

Fig. 3. FIPA compliant agent platform reference model

JADE was used for multi agent implementation because it has an agent platform that complies with FIPA and mainly consists of an agent management system (AMS), a directory facilitator (DF) and a message transport system as shown in Fig. 3. In addition, JADE exhibits numerous inherent features found in distributed systems. Most of JADE's complexities are hidden from users enabling more focus on logical aspects of the system. Furthermore, JADE provides graphical interface for monitoring agents as well as an extensive library of classes with methods based on FIPA standards.

Similarly, MACSimJX was used as the coordination layer because it specifically integrates Simulink with JADE and facilitates the development of software control structures with a range of features [27]. In addition, MACSimJX has a client-server architecture and has the capability of parallel processing information as well as handling multi threaded programs, a requirement for distributed systems.

A. Agents Developed in Proposed MAS

The proposed multiagent system comprises many intelligent agents representing various components in a microgrid. Each agent has a localized knowledge base, containing rules and behaviors, which governs its decision making process. The agent internal process is shown in Fig. 4 which illustrates the states involved when decisions are made.

Microgrid agents developed in the proposed MAS include generation (DG) agents, load (Demand) agents, market clearing engine (MCE) agent, coordination (CO) agent, utility grid (UG) agent, and other ancillary agents. A brief description of the functionalities for the main agents are given below.

DG Agent: This agent models combined heat and power (CHP) units, dispatchable units which may include MTs, fuel cells and energy storage systems and non-dispatchable units which may include PVs and WT as an aggregated equivalent DG unit under the same owner to participate in microgrid market operations through negotiations with Demand Agents. It also regulates and controls output power and status of DG units. Information contained in this agent includes an agent

Fig. 4. Agent process flowchart

identifier, minimum and maximum generation limits and dynamic data such as bidding rate, generation settings, revenue and DG surplus.

Demand Agent: This agent models an aggregated equivalent load unit under the same consumer to participate in market operations through negotiations with DG Agents. It is also capable of regulating and controlling the power demand and status of the respective load units based on energy prices. Information residing in this agent includes an agent identifier, minimum and maximum demand limits and dynamic data such as bidding rate, power demand settings, load costs and savings.

MCE Agent: This agent becomes active if the MCP computation of the microgrid is required for a specified period. It takes in bids from DG and Demand Agents and liaises with CO Agent during market operations. Furthermore, it contains aggregated information on microgrid generation and demand levels.

CO Agent: This agent is responsible for coordinating the entire microgrid market operation as well as monitoring the network for any technical violations. It coordinates with MACSimJX Agent to signal the beginning and end of market operations for that period.

UG Agent: The utility grid agent basically behaves similar to an Independent System Operator (ISO) and is responsible for power balance in the microgrid. It also broadcasts retail price signals to DG and Demand Agents at regular intervals to facilitate decision making in the corresponding agents.

MACSimJX Agent: This agent basically performs coordination between Simulink and JADE as well as manages an Agent Task Force (ATF) which consists of several other ancillary agents. In addition, an Agent Environment (AE) residing within this agent also acts as an interface for coordinating control signals between Simulink and JADE.

B. Agents Interaction and Coordination

A hierarchical control architecture [34, 35] is used for the simulation of microgrid operation. The entire microgrid market operation and simulation are achieved by distributing responsibilities to the various agents. Agents accomplish assigned tasks by proactively interacting among themselves as shown in Fig. 5. From Fig. 5, steps 1 to 7 execute a few hours before gate closure while steps 8 to 10 execute after gate closure, say about an hour before the actual energy delivery. They define the pre-gate and gate closure periods typical in electricity markets.

During initialization, AE will instruct ATF to inform CO Agent to begin market operation. After which, MCE Agent

Fig. 5. Interaction between agents for market operation and implementation requests for DG and Demand Agents bidding data as well as grid pricing data. Once all bids have been received, MCE Agent then computes MCP and informs relevant agents about the results. Every DG and Demand Agent then perform an internal scheduling and concurrently check for any technical violations with its ATF counterpart.

The energy trading which solves a symmetrical assignment problem [17] between DG and Demand Agents will commence after all technical violations have been resolved. DG and Demand Agents will aim at achieving a certain objective based on one of the three agent objectives assigned as described in Section III. Under maximizing DG surplus objective, DG Agents will search through DF and negotiate with every Demand Agent and UG Agent to sell their energy at the highest offered price. Similarly for maximizing load surplus objective, Demand Agents will search through DF and negotiate with every DG Agent and UG Agent to buy energy at the lowest offered price. For maximizing both the DG and load surplus objective, DG Agents, Demand Agents and UG Agent will negotiate among themselves to arrive at a common price that benefits both DG and Demand Agents. UG Agent then performs power balance for the microgrid whose generation or load is still not satisfied after negotiations by either buying back the excess power from DG Agents or selling power to Demand Agents. Market operation ends when DG and Demand Agents inform CO Agent about the trading results and the updated dispatch will be passed on to ATF and AE for implementation in Simulink.

In the event that the power available from/to the grid to/from the microgrid is limited, the UG Agent is first to know the status through the real-time measurement from the smart meter located at the point of common coupling (PCC). Subsequently, the UG Agent will inform every DG and Demand Agent concerning the shortfall/excess in active power at the PCC through JADE and MACSimJX which can provide the basic necessary services for agent communication. At the same time, DG and Demand Agents will also sense a change in the system frequency through the real-time measurement on the respective local controllers. The local DG controllers then perform primary control which actively adjusts by raising/lowering the active power output of each DG until the

system frequency is stabilized. In addition, Demand Agents are expected to perform local voltage control at the load terminals by controlling the amount of injected reactive power from the local capacitor bank. It should also be noted that agents are required to interact and coordinate among themselves via AE, ATF and CO Agent as described in Section IV.A so that the DG and Demand Agents are aware of the system dynamics and are able to make informed control decisions.

V. SIMULATION STUDIES AND RESULTS

A. 7-Bus Microgrid System

Simulation studies were carried out on a three phase, seven-bus, 400V grid-connected microgrid. The microgrid consisting of three equivalent DGs, three dynamic equivalent loads and a utility grid power source was modeled in Simulink. An equivalent single-line diagram is shown in Fig. 6. Details on network parameters and the number of DGs and loads in each equivalent DG and load are given in Table I and Table II. This setup considers a scenario with three DG owners and three load users that serves as a building block for a larger dynamic power system.

In this setup, equivalent DGs and loads ranging from 0.75MW to 3.5MW were connected to the microgrid. Each equivalent DG consists of dispatchable and non-dispatchable units having various sizes. The minimum DG power represents the situation when cogeneration units are programmed to provide minimum heating requirements to the local community. It is the sum of all minimum power requirements of the cogeneration units and minimum power of any on-line units with similar physical constraints under the corresponding DG owner. Conversely, the maximum DG power is the sum of all units' rated power when all units under the respective DG owner participate in market operations. Local voltage regulating devices are placed at load buses to improve load voltage profile when necessary. Network parameters were taken from a typical low voltage distribution network. The no-load price in Table II refers to the price intercept for the

Fig. 6. Single-line diagram of microgrid in Simulink

TABLE I
MICROGRID NETWORK PARAMETERS

LINE PARAMETER	IMPEDANCE (Ω) PER PHASE
Z_{12}	$1+j1.571$
Z_{23}	$0.205+j1.477$
Z_{14}	$2+j1.885$
Z_{45}	$0.205+j1.477$
Z_{16}	$3+j2.2$
Z_{67}	$0.205+j1.477$

TABLE II
DETAILS OF DISTRIBUTED GENERATORS AND LOADS

UNIT TYPE	NUMBER OF UNITS	MIN. POWER (MW)	MAX. POWER (MW)	NO-LOAD PRICE (\$/MWh)
DG 1	400	1	2.75	-
DG 2	700	2	3.25	-
DG 3	550	1.5	3	-
Load 1	300	2	3.5	0.8
Load 2	250	1	3	0.7
Load 3	100	0.75	2.5	0.6

TABLE III
BIDDING RATES (m_g, m_p in \$/MWh/MW) OVER 24-HOUR PERIOD

HOUR	DG 1	DG 2	DG 3	LOAD 1	LOAD 2	LOAD 3
1	0.3125	0.2734	0.2482	0.221	0.152	0.106
2	0.2864	0.2549	0.2019	0.265	0.196	0.157
3	0.2489	0.1986	0.1917	0.288	0.225	0.175
4	0.2168	0.1662	0.1529	0.325	0.269	0.229
5	0.2259	0.1827	0.1717	0.311	0.254	0.205
6	0.2341	0.1955	0.1875	0.292	0.249	0.194
7	0.2626	0.2185	0.2089	0.277	0.201	0.167
8	0.2978	0.2637	0.2314	0.247	0.173	0.141
9	0.1874	0.1596	0.1545	0.042	0.033	0.014
10	0.2136	0.1775	0.1924	0.118	0.081	0.055
11	0.2316	0.2072	0.1899	0.127	0.095	0.079
12	0.1956	0.1671	0.1717	0.092	0.077	0.047
13	0.1782	0.1419	0.1574	0.078	0.054	0.02
14	0.2121	0.1836	0.1985	0.115	0.085	0.056
15	0.2015	0.1735	0.1833	0.101	0.091	0.064
16	0.2584	0.2263	0.2044	0.172	0.151	0.123
17	0.2252	0.1989	0.1822	0.188	0.141	0.13
18	0.2445	0.2112	0.1984	0.166	0.141	0.112
19	0.1928	0.1731	0.1631	0.112	0.104	0.096
20	0.2147	0.1884	0.1726	0.141	0.122	0.132
21	0.2033	0.1798	0.1677	0.124	0.113	0.105
22	0.2626	0.2332	0.1988	0.277	0.175	0.146
23	0.2594	0.2461	0.2144	0.281	0.195	0.189
24	0.2911	0.2679	0.2338	0.255	0.188	0.138

corresponding loads as described in (2). The utility grid acts as a power balancing source to maintain power balance in the microgrid during normal operation.

Simulation studies for a typical day were carried out. The 24-hour bidding rates for DGs and loads are given in Table III. Results of market clearing prices and grid prices [41] for a typical day are shown in Fig. 7. High grid prices are observed between 0800h to 1600h which also coincide with the peak hours of a study day. Bidding patterns of DGs and loads also follow grid pricing trend resulting in MCP having a similar price trend during the same period.

Fig. 8 shows the simulation results of DG scheduling and power supplied by the utility grid for the same study day. Between 0000h to 0800h and 2100h to 2400h, DG 2 was scheduled to generate 2MW. At 0800h and 1200h, DG 2 was scheduled at 3.25MW. Likewise, DG 1 and DG 3 were also scheduled accordingly. All DGs operate within the MW limits shown in Table II. By observing the power generated from the utility grid at the various hourly intervals, the microgrid experiences different conditions during the study day. A slight variation in utility grid power is observed at each hour to maintain power balance in the microgrid except at 0800h when the microgrid has excess generation and exports 1MW back to the utility grid. At 0900h, the microgrid's generation and load demand are balanced resulting in no power exchange from the

Fig. 7. Grid and market clearing prices

Fig. 8. Simulated DG scheduling

Fig. 9. Simulated load scheduling and system losses utility grid. At 2100h, the microgrid experiences a slight shortage in generation and imports about 0.07MW from the utility grid to maintain power balance. This shows that the power management by the agents is able to handle various microgrid conditions.

Fig. 9 shows the outcome of load scheduling and system losses for the day. Between 0000h to 0800h and 2100h to 2400h, it is observed that Load 1 requires a constant 2MW which shows that the simulated load scheduling works as the minimum power for Load 1 has been reached. Similarly, Load 2 reaches maximum demand of 3MW at 0800h and 1200h while Load 3 reaches peak demand of 2.5MW at 1200h. The first system load peak occurs from 0800h to 1500h. Its peak behaviors coincide with peak DG generation and high grid retail price in Fig. 8 and Fig. 7 respectively. The second load peak occurs from 1800h to 2100h whose behaviors coincide with the second DG generation peak but at a lower grid retail price. The total system power losses remain around 0.1MW throughout the day and account for approximately 3% of the total load demand.

Fig. 10. DG 1 active power response during 1500h

Fig. 11. Load 1 per unit voltage profile during 1500h

From Fig. 9, it is observed there is a sudden drop in load demand at the beginning of 1500h since the market clearing engine is assumed to clear once for each hourly interval. In reality, the real-time load will change gradually over the entire hour and the load increment/decrement will not be so sudden and huge. The DGs respond to the sudden load drop by adjusting their active power reference settings accordingly. From Fig. 8, DG 1 changes its production from 2.35MW to 1.62MW while DG 2 changes from 2.73MW to 2MW and DG 3 changes from 2.59MW to 2.05MW to accommodate the change in load at 1500h. DG 1 is modeled as an equivalent power electronics generator in the simulation of this paper. From Fig. 10, DG 1 generates 2.35MW in the previous hour until at 1500h, its generation decreases to 1.65MW within 0.5 seconds to meet the new operating condition. This shows the fast response of the DG for dynamic microgrid operation.

In Fig. 11, it is observed that the per unit voltage at Load 1 terminal at 1500h rises momentarily by about 0.6% to 1.006 p.u. during the first 0.04 seconds before settling down at about 1 p.u. after 0.2 seconds. The voltage rise is attributed to the sudden drop in load demand while the system takes some time for the dynamics to settle down before it reaches a new steady-state operating condition. During transition, a brief period of excess generation causes the load terminal voltage to rise momentarily.

Fig. 12. DG 1 profits with different agent objectives over a study day

Fig. 13. Load 1 savings with different agent objectives over a study day

The afterwards effect on voltage is regulated at 1 p.u. which is maintained by a local capacitor bank.

Comparisons of DG profit and load savings under different agent objectives are given in Fig. 12 and Fig. 13. Fig. 12 shows a snapshot of DG 1 profits for different agent objectives in the same study day. A base objective where agents trade directly with the utility grid and do not participate in the microgrid market operations is used for comparison. It is observed from Fig. 7 that during periods where MCP is below the grid retail price, DG 1 agent reports similar profits when assigned under the agent maximization objectives. However, during periods where MCP is above the grid retail price, DG 1 agent reports varying profit levels when assigned different agent objectives. In addition, DG 1 agent reports negative profits during certain periods when assigned the load surplus maximization or base objective indicating that the generation cost is higher than the revenue. This shows that the grid price can affect DG profits.

TABLE V
DISTRIBUTED GENERATORS REVENUE AND PROFIT OVER 24-HOUR PERIOD

UNIT TYPE	MAX. LOAD SURPLUS		MAX. DG SURPLUS		MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)
DG 1	16.45	7.24	18.74	9.53	17.60	8.39	9.69	0.48
DG 2	19.43	6.85	22.45	9.87	20.94	8.36	11.76	-0.82
DG 3	18.63	7.73	21.41	10.51	20.02	9.12	11.14	0.25
Total	54.51	21.82	62.60	29.91	58.56	25.87	32.59	-0.09

TABLE VI
LOAD ENERGY COSTS AND SAVINGS OVER 24-HOUR PERIOD

LOAD TYPE	MAX. LOAD SURPLUS		MAX. DG SURPLUS		MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)
Load 1	23.91	11.36	25.07	10.19	24.49	10.77	31.24	4.02
Load 2	20.83	7.67	21.81	6.69	21.32	7.18	27.32	1.18
Load 3	16.39	3.81	17.17	3.02	16.78	3.41	21.26	-1.07
Total	61.13	22.84	64.05	19.90	62.59	21.36	79.82	4.13

Similarly, Fig. 13 shows a snapshot of Load 1 savings when subjected to different agent objectives for the same study day. Load 1 agent reports similar savings whenever MCP is below grid retail price and varying level of savings when MCP is higher than the grid retail price. Load 1 agent also reports negative savings between 0800h and 1400h when the agent was assigned the base objective. Referring to Fig. 7, the negative savings are attributed to high grid retail prices during the same period which results in a higher amount payable by Load 1 as compared to the load cost.

Numerical results for DG revenues and profits as well as load costs and savings over a 24-hour period are given in Table V and Table VI. Table V shows the revenue and profit for each DG as well as the aggregated amount. In general, DG agents have a better profit when agents are assigned optimization objectives compared to the base objective. Although maximizing DG surplus yields the highest profit, load savings are minimized simultaneously. This shows that maximizing DG surplus favors the generation side and likewise maximizing load surplus favors the load side. However, DG agents assigned to maximizing the DG and load surplus objective yield optimal profits which maximize both the DG profits and load savings simultaneously. It is also observed that DG 2's profit is negative under the base objective. This indicates that DG 2 has accumulated a net negative profit of -\$0.82 over the 24-hour period which is due to a higher generation cost compared to the revenue collected.

Table VI shows the load costs and savings for each load agent under different agent objectives. It is observed that load agents assigned to maximizing the DG and load surpluses yield optimal savings. In addition, load savings are significantly higher when load agents are assigned the optimization objectives compared to base objective. Load 3 has negative savings under the base objective indicating that the amount payable by Load 3 is higher than the load cost. Since Load 1 reports the highest savings under the base objective, the total load savings for the microgrid remains positive despite negative savings from Load 3.

From the results in Table V and Table VI, it is evident that maximizing both DG and load surplus objective provide optimal benefits to both the DGs and the loads and is not biased to either side. Similar trends are also observed for each hour during the study day. During each hourly interval, DG and Demand Agents coordinate and trade according to assigned agent objectives. At the end of each trading session, the UG Agent maintains power balance by accepting all sale requests from DG agents having excess generation and accepting all purchase requests from Demand Agents having unsatisfied load. This shows the effectiveness of agents in handling various conditions.

B. Extended Analysis on IEEE 14-Bus Test System

The proposed approach is further tested on a modified IEEE 14-bus test system [40]. In this system, there is one utility grid generator, four DGs and eleven loads. The utility grid generator is located at bus 1 which is also the reference bus.

TABLE VII
RESULTS OF DG AND LOAD FOR 14-BUS SYSTEM OVER 24-HOUR PERIOD

HOUR	DG AT BUS 3			LOAD AT BUS 9			MCP (\$/MWH)
	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	
1	0.468	0.0249	0.45	0.295	-0.0091	0.44	0.44
2	0.415	0.0293	0.44	0.285	-0.0011	0.43	0.43
3	0.377	0.0239	0.43	0.272	-0.0038	0.42	0.42
4	0.320	0.0275	0.41	0.258	-0.0128	0.39	0.40
5	0.488	0.0248	0.44	0.272	-0.0136	0.42	0.43
6	0.431	0.0324	0.50	0.286	-0.0002	0.48	0.48
7	0.667	0.0207	0.60	0.340	-0.0114	0.58	0.59
8	0.365	0.0362	0.62	0.381	0.0040	0.60	0.60
9	0.524	0.0361	0.65	0.408	0.0063	0.63	0.63
10	0.778	0.0383	0.67	0.476	0.0010	0.65	0.65
11	0.958	0.0435	0.69	0.517	0.0084	0.67	0.66
12	1.079	0.0447	0.71	0.544	0.0143	0.69	0.68
HOUR	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	MCP (\$/MWH)
13	0.895	0.0411	0.67	0.530	0.0114	0.65	0.64
14	0.956	0.0362	0.65	0.530	0.0052	0.63	0.63
15	0.889	0.0352	0.63	0.517	0.0084	0.62	0.61
16	0.778	0.0395	0.61	0.476	-0.0004	0.59	0.59
17	0.889	0.0324	0.67	0.517	-0.0020	0.65	0.65
18	0.817	0.0437	0.71	0.585	0.0047	0.68	0.68
19	0.556	0.0508	0.67	0.558	0.0102	0.65	0.64
20	0.444	0.0535	0.65	0.544	0.0109	0.63	0.62
21	0.333	0.0529	0.63	0.490	0.0096	0.61	0.60
22	0.222	0.0394	0.58	0.422	0.0004	0.56	0.56
23	0.419	0.0257	0.51	0.34	-0.0086	0.50	0.50
24	1.108	-0.0126	0.46	0.30	-0.0229	0.46	0.47

TABLE VIII
MARKET RESULTS FOR 14-BUS SYSTEM OVER 24-HOUR PERIOD

DG LOCATION	MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)
Bus 2	7.79	5.56	4.77	2.54
Bus 3	6.33	5.08	3.44	2.20
Bus 12	2.79	2.09	1.33	0.63
LOAD LOCATION	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)
Bus 2	4.30	0.73	4.40	0.64
Bus 3	18.20	5.44	18.29	5.34
Bus 4	9.55	3.07	9.61	3.01
Bus 5	2.81	0.09	2.83	0.08
Bus 6	3.60	0.03	3.69	-0.05
Bus 9	5.91	0.84	6.01	0.74
Bus 10	3.06	0.11	3.13	0.04
Bus 11	2.15	0.07	2.17	0.06
Bus 12	2.58	0.06	2.62	0.03
Bus 13	1.94	0.12	1.98	0.08
Bus 14	5.49	0.90	5.51	0.87

The four DGs are located at buses 2, 3, 4 and 12. The eleven loads are located at buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14. The utility grid generator is represented by a UG Agent. Each DG is represented by a DG agent and each load by a Demand Agent. Generator and load data is obtained from [40]. The line parameters are obtained from the IEEE 14-bus test system [42].

The dispatched power, marginal loss factor values, LMP and MCP over a 24-hour period are shown in Table VII. There are four DG Agents and eleven Demand Agents in the 14-bus test system. Results for the DG connected at bus 3 and the load at bus 9 are shown in Table VII. It can be observed that the LMP values differ slightly from MCP due to the contribution of marginal loss factors. Positive marginal loss factor values indicate that the change in power injection at the

corresponding bus results in an increase of system losses while negative values indicate a reduction of system losses due to a change in power injection at the bus. Based on the values obtained, DGs will fetch a higher price for positive marginal loss factor and will fetch a lower price for negative values. Conversely, loads will be penalized for positive marginal loss factors and rewarded for negative values according to (7) when the energy trading algorithm is executed.

Market results for DG and Demand Agents for the 14-bus test system over a 24-hour period is shown in Table VIII. The maximization of DG and load surplus objective was compared with the base objective. There are no market results for the DG connected at bus 4 because it is the most expensive unit and did not participate in the market operation during the 24-hour period. From Table VIII, when compared to the base objective, it is observed that DGs yield higher profits and loads have higher savings. They follow the same trend as those of the 7-bus microgrid system.

VI. CONCLUSION

This paper presents a MAS approach for distributed management of microgrids. The proposed MAS was developed using IEEE FIPA standards, and market operations were coordinated with implementation of the microgrid. Simulation studies and results demonstrate the effectiveness of the proposed distributed market operation and control technique displaying much potential for the autonomous operation of microgrids. It is found that maximizing the benefit for both energy buyers and sellers promotes unbiased transactions between them. The proposed market structure can be extended to manage a larger network comprising numerous participants. Furthermore, the proposed approach can be implemented in actual microgrids with minimal additional software cost by replacing the Simulink models with the actual microgrid and the communication network interface between MACSimJX and actual microgrids can be achieved through TCP/IP and the necessary SCADA I/O devices. Simulation studies have shown that the proposed distributed system is capable of handling the economical and technical requirements of microgrids. Coordination of multiple microgrids will be considered in the future which will reinforce the research and development of smart grids.

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