Multiagent System for Real-Time Operation of a Microgrid in Real-Time Digital Simulator

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***Abstract*—This paper presents a multiagent system (MAS) for real-time operation of a microgrid. The proposed operational strategy is mainly focused on generation scheduling and demand side management. In generation scheduling, schedule coordinator agent executes a two-stage scheduling: day-ahead and real-time scheduling. The day-ahead scheduling finds out hourly power settings of distributed energy resources (DERs) from a day-ahead energy market. The real-time scheduling updates the power settings of the distributed energy resources by considering the results of the day-ahead scheduling and feedback from real-time operation of the microgrid in real-time digital simulator (RTDS). A demand side management agent performs load shifting before the day-ahead scheduling, and does load curtailing in real-time whenever it is necessary and possible. The distributed multiagent model proposed in this paper provides a common communication interface for all components of the microgrid to interact with one another for autonomous intelligent control actions. Furthermore, the multiagent system maximizes the power production of local distributed generators, minimizes the operational cost of the microgrid, and optimizes the power exchange between the main power grid and the microgrid subject to system constraints and constraints of distributed energy resources. Outcome of simulation studies demonstrates the effectiveness of the proposed multiagent approach for real-time operation of a microgrid.**

***Index Terms*—Distributed energy resources, microgrid, multiagent system, real-time digital simulator, real-time operation.**

I. Introduction

SMART GRID [1] represents a vision for the future power distribution systems, which integrates advanced sensing technologies, control methodologies and communication technologies into current electricity grid. Microgrid [2], [3] is an innovative control and management architecture at distribution level, which makes it easy to implement smart grid techniques at distribution level.

The traditional energy management system (EMS) [4] mainly consists of three components: System Control And Data Acquisition (SCADA) system, state estimator (SE), and contingency analyzer (CA). SCADA system serves as both data gathering system and device control system. Data is collected from generation plants and substations through field remote terminal units (RTUs) and then fed into master stations integrated in the control room of each control area. SE is used in the control room to improve the accuracy of the raw sampled data by mathematically processing it to make it consistent with the electrical system model. The resulting information for equipment voltages and loadings is used in software tools like CA to simulate various conditions and outages to evaluate the reliability of the power system.

Operation of modern power systems [5], [6] becomes extremely complex with the introduction of distributed power generation, load control, market operation, increasing complexity of distribution networks, and a large number of interconnections. Consequently, real-time control and management of modern power systems [7], [8] has become more complex. Therefore, smart control and energy management [4], [9], [10] systems that are different from those commonly used in the past are necessary for efficient operation of modern power systems. Control area operators need to have necessary capabilities to obtain real-time status information of the equipment and system components, adequately assess the system state, and predict trends before the fact to respond rapidly even before events start to unravel, and perform coordinated actions in real-time across the service area. At the device level, hardware should have the capability to provide reactive power, frequency control and voltage control according to system needs and correspondingly, rapidly reconfigure the system to a secure state through disconnect switches, circuit breakers and power-electronics based devices. Most of these requirements can be achieved by providing a common communication interface [11], [12] for all physical elements in the power systems.

Intelligent multiagent-based [13] modeling of power systems is a promising approach to provide a common communication interface for all agents representing the autonomous physical elements in the power system. Furthermore, the distributed nature and potential for modeling autonomous decision making entities in solving complex problems motivates the use of multiagent system for the operation of modern power systems through implementing smart grid techniques. Even though some researches [14]–[21] on this potential approach have started in various places, most of these reported multiagent systems are not implemented based on any industrial standards. In addition, no proper multiagent system was implemented for real-time operation of the modern power systems even though the real-time study is necessary for the real reliable operation.

This paper proposes a multiagent system for real-time control and management of a microgrid using RTDS [22] under simulated real-time operational conditions. The multiagent system was developed in JADE [23] which is a Foundation for Intelligent Physical Agents (FIPA) [24] compliant open source multiagent platform. Agents in the multiagent system interact cooperatively [25] to optimize the operation of the microgrid. Mainly two functions of the microgrid operation, demand side management and generation scheduling, were demonstrated.

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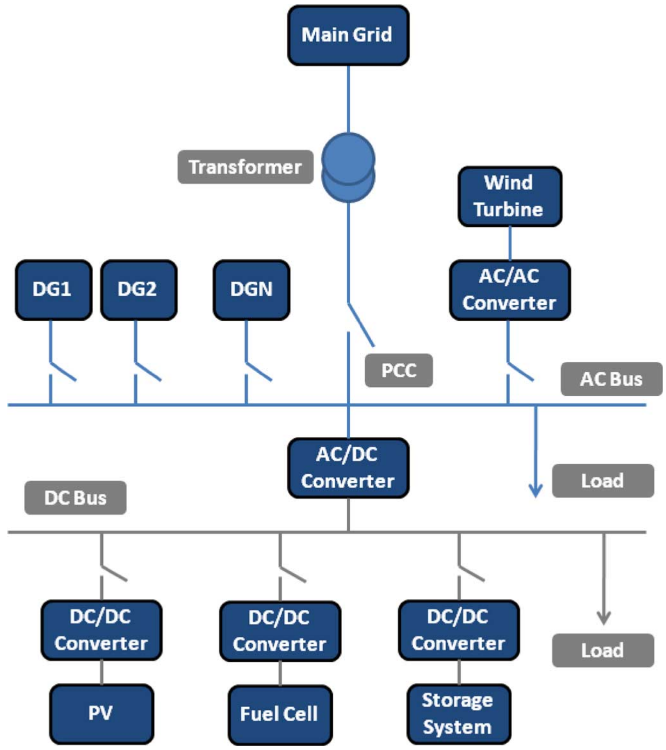

Fig. 1. Schematic diagram of a hybrid microgrid.

Demand side management [26], [27] plays an important role in smart grid operation. Controlling energy demand 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 construction of an under-utilized electrical infrastructure in terms of generation capacity, transmission lines and distribution networks. Generation scheduling [25] determines the schedule of generation units within the microgrid subject to operational constraints of the microgrid and generation units. Significant cost savings can be achieved by optimizing the generation schedules over the planning horizon.

The remaining paper is organized as follows. Section II briefly explains the control and management of a microgrid. Section III formulates the problems mathematically. Section IV explains the proposed multiagent system architecture. Section V provides simulation studies and results. Section VI concludes the paper.

II. Microgrid Control and Management

A schematic diagram of a hybrid microgrid architecture is shown in Fig. 1.

Micrograds can be operated as grid-connected systems in parallel with the main distribution grid, or as islanded systems if they are disconnected from the main distributed grid. 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 among the various elements.

A. Microgrid Management

As stated above, microgrid [2], [3] can operate in both grid-connected and islanded modes. Its functionalities and control structure depend on the mode of operation. The main objective of the microgrid management is to optimize the local production in both modes of operation. Some of the typical microgrid managerial functions are forecasting of electrical load and heat demand, forecasting of power production capabilities of renewable energy sources, economical generation scheduling including load shedding and emissions calculations, demand side management, and security assessment. An overview of the specific functionalities of microgrid in each mode is given briefly in the following sections.

Islanded Mode: In islanded mode, two requirements must be fulfilled due to the unavailability of the utility grid: Power balance between generation and load demand, and control of voltage amplitude and frequency of the installation. Controllable micro sources such as engine generator, fuel cell, and energy storage system are responsible for ensuring the power balance by means of absorbing or injecting the power difference between the renewable generation and local loads because renewable energy sources are noncontrollable energy sources. In case of excess energy, the management system has to decrease the output power of the controllable micro sources to maintain the frequency and voltage of the microgrid. On the other hand, if the available power is not enough to feed the local loads, the management system will detach noncritical loads. In addition, functions such as islanding, synchronizing of the microgrid with the main grid, and black start capabilities are required to be handled by microgrid in islanded mode.

Grid-Connected Mode: In grid-connected mode, power balance between generation and load demand, and the control of the parameters are guaranteed by the utility grid. Thus, generators are regulated with the criterion of optimized economic exploitation of the installation. Renewable energy sources are considered more economical to generate energy locally than to buy from the utility grid. Therefore, their references are calculated with the objective of extracting the maximum power from renewable sources. In grid-connected mode, microgrid operates as a constant power generator or a constant power load, and as a filter for the active power injection to the utility grid or absorption from the utility grid.

B. Microgrid Control

Microgrid controllers [2], [3] are responsible for ensuring that micro sources work properly at or near predefined operating points while satisfying the operating limits of the micro sources. Microgrid control system is needed to handle the power transfer according to necessity of the microgrid, disconnection and reconnection processes, market participation, and heat utilization for local installations. Furthermore, the microgrid control system is able to operate through black-start. Microgrid controls can be classified as local controls, centralized controls or decentralized controls according to the decentralization of responsibilities and functions of the controllers.

III. Problem Formulation

In this paper, an intelligent multiagent system is proposed for demand side management and generation scheduling functions of microgrid management. Generator agents retrieve power scheduling information, and send the set points to the generators. A two-level generation scheduling system, with day-ahead scheduling and real-time scheduling, is used in this paper. Day-ahead scheduling is carried out for short-term generation scheduling, and real-time scheduling performs suitable corrections over the day-ahead schedules by analyzing

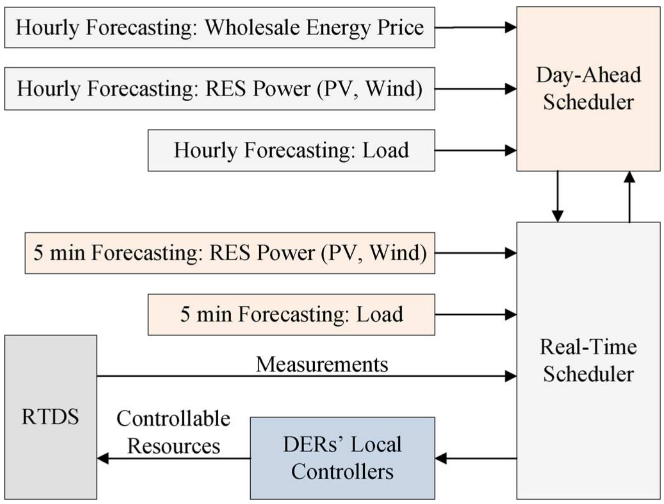

Fig. 2. Proposed real-time operational architecture of a microgrid.

these schedules and real-time measurements. Demand side management agent performs load shifting and load curtailment. Load shifting algorithm is run a day in advance to optimize the connection of controllable loads in accordance with some optimization criteria. Load curtailment decreases the power consumption of the controllable loads dynamically during the real-time operation of the microgrid.

Fig. 2 shows the schematic diagram of the proposed real-time operational architecture of microgrid.

A. Demand Side Management Problem

The proposed demand side management (DSM) technique [28] schedules 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 objective load consumption curve is generated according to the criteria for deciding the optimal load consumption. The criteria could be maximizing the use of renewable energy resources, maximizing the economic benefit by offering bids to reduce demand during the peak periods, minimizing the amount of power imported from the main grid, or reducing peak load demand. The problem is mathematically formulated as a minimization problem and is given as follows.

Minimize

$$\sum_{t=1}^{N}\left(PLoad(t) - Objective(t)\right)^2 \tag{1}$$

where $Objective(t)$ is the value of the objective curve at time t, and $PLoad(t)$ is the actual consumption at time t, which is given by the following equation:

$$PLoad(t) = Forecast(t) + Connect(t) - Discont(t) \tag{2}$$

where $Forecast(t)$ is the forecasted load consumption at time t, and $Connect(t)$ and $Discont(t)$ are the amounts of load connected and disconnected at time t respectively during the load shifting.

$Connect(t)$ is made up of two parts: the increment in load at time t due to the connection times of devices shifted to time t, and the increment in load at time t due to the device connections scheduled for times that precede t, which is given by the following equation:

$$Connect(t) = \sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{kit}.P_{1k} + \sum_{l=1}^{j-1}\sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{ki(t-1)}.P_{(1+l)k} \tag{3}$$

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_{1k} and $P_{(1+l)k}$ are the power consumptions 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 $Discont(t)$ also consists of two parts: the decrement in the load at time t 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 at time t due to delay in connection times of devices that were expected to start their consumption at time steps that precede t, and is given by the following equation:

$$Discont(t) = \sum_{q=t+1}^{t+m}\sum_{k=1}^{D} X_{ktq}.P_{1k} + \sum_{l=1}^{j-1}\sum_{q=t+1}^{t+m}\sum_{k=1}^{D} X_{k(t-1)q}.P_{(1+l)k} \tag{4}$$

where X_{ktq} is the no of devices of type k that are delayed from time step t to q, and m is the maximum allowable delay.

This minimization problem is subject to the following constraints.

Number of devices shifted cannot be a negative value.

$$X_{kit} > 0 \qquad \forall i, j, k. \tag{5}$$

Number of devices shifted from a time step cannot be more than the number of devices available for control at that time step.

$$\sum_{t=1}^{N} X_{kit} \leq Ctrlable(i) \tag{6}$$

where $Ctrtable(i)$ is the number of devices of type k available for control at time step i.

In addition, DSM agent curtails load to decrease the power consumption of the controllable loads during the real operation of the microgrid whenever it is necessary and possible.

B. Day-Ahead Scheduling Problem

A schematic diagram of the microgrid is shown in Fig. 3 to illustrate the formulation of the problem.

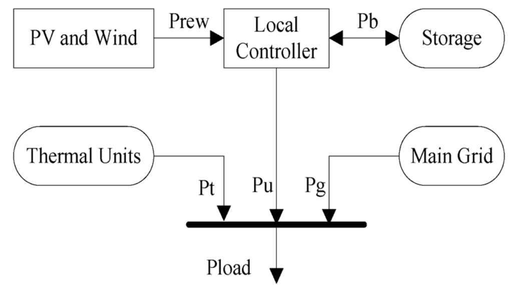

Fig. 3. Schematic diagram of a typical microgrid.

Day-ahead scheduling [25], [29] of a microgrid is mathematically formulated as follows.

The microgrid sells power to its internal loads at market prices, and exchanges power with the main grid at market prices. When the power produced by generating sources in the microgrid is not enough, or too expensive to cover the internal loads, power P_g is bought from the upstream network, and sold to loads at the same price. The microgrid maximizes its profit by maximizing the revenues and exchanging power with the main grid. The profit of the microgrid is found as follows:

$$\Pr ofit = \text{Revenue} - Expenses \tag{7}$$

$$\Pr ofit = \left[A \times P_g + A \times \sum_{i=1}^{N} P_i\right] - \left[\sum_{i=1}^{N} bid(P_i) + A \times P_g\right] \tag{8}$$

$$\Pr ofit = A \times \sum_{i=1}^{N} P_i - \sum_{i=1}^{N} bid(P_i) \tag{9}$$

where A is the open market price, P_i is the power from source i, N is the number of sources that offer bids for power production, and $bid(P_i)$ is the bid from source i.

This maximization problem is subject to a system constraint which can be written as

$$P_g(t) + \sum_{i=1}^{N} P_i(t) \geq P_l(t) \tag{10}$$

where $P_l(t)$ is the internal load of the microgrid.

In addition, the maximization problem is subject to the technical limits of each unit which are given as follows:

$$\text{(i)} \quad P_u(t) = P_l(t) - P_T(t) \tag{11}$$

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

$$\text{(ii)} \quad P_{\text{Rew}}(t) - P_b(t) - P_u(t) = 0 \tag{12}$$

where $P_{Rew}(t)$ is the total renewable power, and $P_b(t)$ is the battery power at time t.

$$\text{(iii)} \quad P_{\text{Rew}}(t) = P_{pv}(t) + P_{wind}(t) \tag{13}$$

where $P_{pv}(t)$ is the total photovoltaic power, and $P_{wind}(t)$ is the total wind power at time t.

$$\text{(iv)} \quad P_{pv}(t) = f\left(G_a(t), T_a(t)\right) \tag{14}$$

where $G_a(t)$ is the total insolation on photovoltaic plant, and $T_a(t)$ is ambient temperature at photovoltaic plant at time t.

$$\text{(v)} \quad P_{wind}(t) = f\left(V_w(t)\right) \tag{15}$$

where $V_w(t)$ is the wind speed at wind plant at time t.

$$\text{(vi)} \quad P_u(t) < P_u^{\max} \tag{16}$$

where P_u^{max} is the maximum renewable-battery penetration in the microgrid.

$$\text{(vii)} \quad -P_b^{\max} < P_b(t) < P_b^{\max} \tag{17}$$

where P_b^{max} is the maximum battery power.

$$\text{(viii)} \quad C(t) = C(t-1) + \left[\frac{\Delta t \times \eta_b(t)}{V_b(t)} \times \left(P_{\text{Rew}}(t) - P_u(t)\right)\right] \tag{18}$$

where $C(t)$ and $C(t-1)$ represent battery charges at time t and $(t-1)$ respectively, $\eta_b(t)$ the battery efficiency, and $V_b(t)$ is the voltage at battery terminals at time t.

$$\text{(ix)} \quad C(t)\big|_{t=0} = C_0 \tag{19}$$

where C_0 is the initial battery charge.

$$\text{(x)} \quad C(N) = C_f \tag{20}$$

where C_f is the final battery charge.

$$\text{(xi)} \quad C_{\min} < C(t) < C_{\max} \tag{21}$$

where C_{max} is the maximum battery charge, and C_{min} is the minimum battery charge.

Furthermore, this maximization problem is subject to other constraints [25] of the distributed generators such us fuel limits, generation limits, and ramp up and ramp down limits.

C. Real-Time Scheduling Problem

According to the operational strategy proposed in this paper, the real-time scheduling matches the supply and demand of the microgrid in five minute intervals by taking the feedback from the real-time simulation of the microgrid in RTDS, and forecasted data at 5 min intervals. This provides continuous matching of supply and demand in the microgrid.

The real-time supply and demand matching is mainly monitored and controlled by the storage agent. When the real-time matching goes beyond the capacity of the storage agent, the estimated error is calculated in each time step, and adjustments of power settings of sources are assigned to each source in proportion to their maximum generation capacities [8]. The adjustment in power setting ΔP_i^{Assig} for source i is given by the following equation:

$$\Delta P_i^{Assig} = \frac{\left(P_i^{\max} - P_i^{sch}\right)}{\sum \left(P_i^{\max} - P_i^{sch}\right)} \times \sum \left(P_i^{sch} - P_i^{meas}\right) \tag{22}$$

where P_i^{sch} is the scheduled power, P_i^{max} is the maximum power limit for the current market price, and P_i^{meas} is the measured power from the simulation.

This is subject to system constraints and unit constraints which are given in the day-ahead scheduling problem. Whenever the real-time matching goes beyond the capacity of both the storage agent and other distributed sources, demand side management agent curtails load to decrease the power consumption of the controllable loads if it is possible for the reliable operation of the microgrid.

IV. Proposed Multiagent System

The multiagent system proposed for simulating the real-time operation of microgrid in real time digital simulator (RTDS) [22] is shown in Fig. 4.

Fig. 5 shows the layered architecture proposed for real-time control and management of the microgrid. The multiagent system provides a common communication interface for all agents representing the autonomous decision making elements

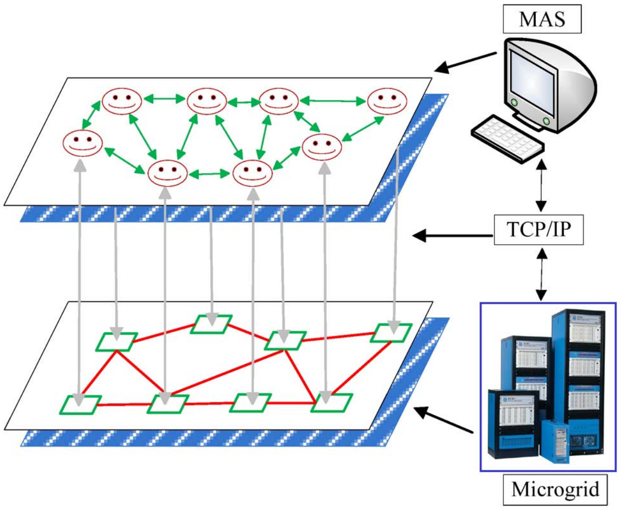

Fig. 4. Schematic diagram of the system.

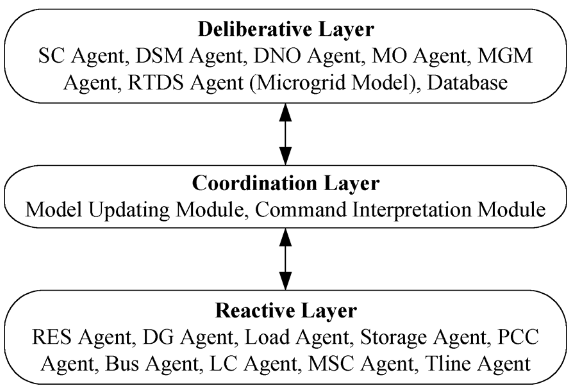

Fig. 5. Layered architecture of MAS.

in the microgrid. The proposed multiagent system was developed according to IEEE FIPA standards [24]. The multiagent system was implemented in JADE [23] platform and was interfaced with RTDS via TCP/IP protocol.

The microgrid was created in RTDS by arranging electrical components from the customized component model libraries. Insolation and temperature for the photovoltaic system, and wind speed for the wind turbine were interfaced through the analogue input ports of RTDS. During the microgrid operation, the multiagent system uses RTDS to confirm the real-time operation without violating any technical constraints.

The functions of each agent are defined according to the proposed control architecture [14]–[16]. Each agent has the autonomy to perform its functions which are constructed by a number of behaviours. Generic architecture of an intelligent agent in this multiagent system is shown in Fig. 6.

The multiagent system consists of intelligent agents representing autonomous elements in the microgrid, administrative agents for managing real-time operation of the microgrid, and agents for managing the multiagent system framework. Each agent has its own knowledge base containing rules. The decision making modules of the intelligent agents were implemented using computational intelligence techniques and mathematical tools. Agent communication was implemented according to FIPA standards.

A. Agents in the Proposed MAS

The multiagent system consists of several distributed generator agents (DG Agent), load agents (Load Agent), 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 demand side management agent (DSM Agent), and other administrative agents. In addition, it has a distributed database which stores data and information regarding all available agents, their tracks, and capabilities. A brief description of the main agents is given below.

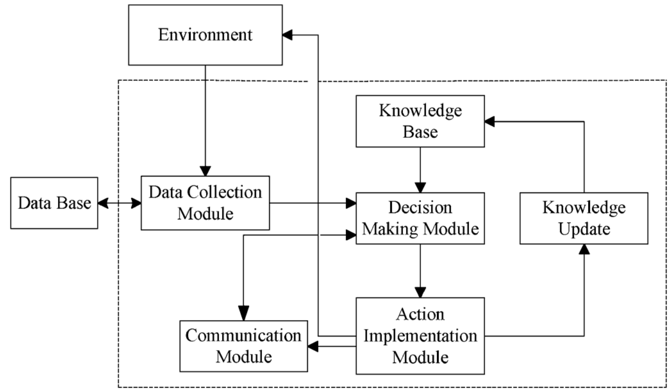

Fig. 6. Generic architecture of an intelligent agent.

MGM Agent: This is the main agent responsible for controlling and managing the microgrid. Monitoring, scheduling and managing the distributed energy resources, and performing demand side management are some of the main functions of this agent.

SC Agent: SC Agent is activated by MGM Agent whenever generation scheduling is necessary for a period. This agent coordinates and negotiates with DG Agents and Load Agents to determine the most economical schedule for the period.

DSM Agent: This agent is responsible for demand side management of the microgrid. In this project, this agent runs a day-ahead load shifting technique optimized by a Genetic Algorithm (GA), and performs load curtailment dynamically.

DG Agent: This is responsible for monitoring, controlling and negotiating the power level and status of the distributed generator it represents. This agent has fixed data such as unit name, minimum and maximum power limits, fuel cost coefficients, and variable data such as power setting and status.

RES Agent: This is responsible for monitoring, controlling and negotiating the power level of renewable energy sources. This agent is interfaced with another database to obtain relevant meteorological data for feeding to the renewable energy source models.

Load Agent: The load agent is capable of monitoring, controlling and negotiating power level of the corresponding load and its status. It acts based on the commands received from the DSM Agent.

Storage Agent: This composite energy storage system (CESS) agent manages the battery banks in the microgrid. This agent monitors state of charge (SOC) of CESS, and responds to the current SOC and requests from MGM Agent.

RTDS Agent: It represents the microgrid in real-time digital simulator into the multiagent system.

B. Coordination Among Agents

A decentralized control architecture [14], [16], [25] is used for operation of the microgrid. As per the functionalities defined in the control architecture, the microgrid manager performs the functions of distribution network operator (DNO) and market operator (MO), which behave in a manner similar to the independent system operator (ISO) and power exchange

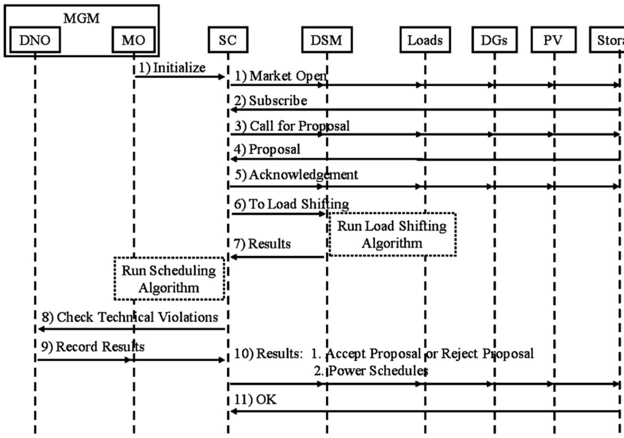

Fig. 7. Interaction of agents for day-ahead scheduling.

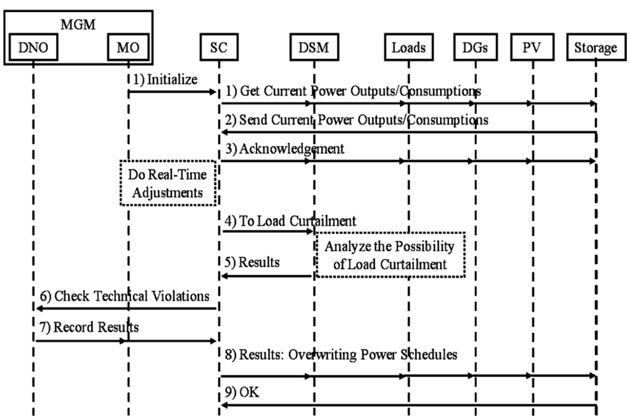

Fig. 8. Interaction of agents for real-time scheduling.

TABLE I
DETAILS OF THE DISTRIBUTED ENERGY RESOURCES

Unit Type	Min. Power (kW)	Max. Power (kW)	Operational Cost $(a+bP+cP^2)$		
			a	b	c
Fuel Cell	30	60	0.38	0.0267	0.00024
DG 1	50	200	0.40	0.0185	0.00042
DG 2	20	60	0.65	0.0152	0.00052
DG 3	20	140	0.30	0.0297	0.00031
PV	0	150	-	-	-
Battery	0	65kW, 650kWh	-	-	-

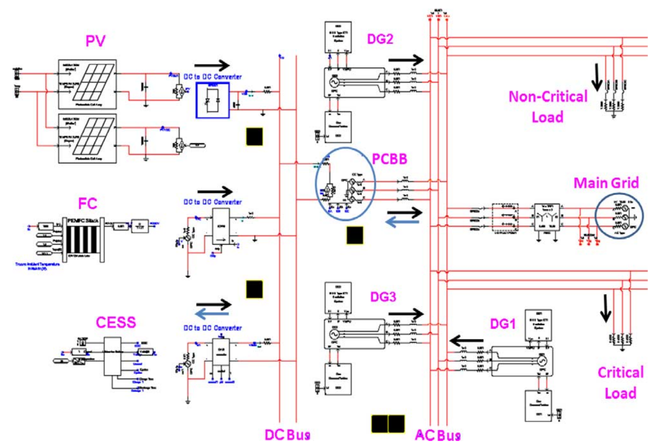

Fig. 9. Electrical network of the microgrid in RTDS.

(PX) in the deregulated power system respectively. First, DSM Agent carries out load shifting according to the wholesale electricity prices to minimize the operational cost, then the day-ahead scheduling is carried out based on the day-ahead microgrid market.

In the day-ahead scheduling, distributed generators submit their hourly bids to supply power over a 24-h window. The MO handles the scheduling based on the bidding and operating cost of generators. The DNO finalizes the schedules without any violation of technical constraints. Finally, the real-time scheduling is carried out as proposed in the paper, and the power settings of the distributed energy resources are adjusted according to the proposed real-time management strategy. Load curtailment is carried out by the DSM Agent whenever it is necessary and feasible while ensuring that the system operates reliably.

In this simulation platform, intelligent agents interact with other agents proactively. Interaction of agents and respective messages for the day-ahead generation scheduling and load shifting are shown in Fig. 7.

This loop runs only once a day to obtain generation schedules for the following day. Interaction of agents and respective messages for the real-time generation scheduling and load curtailment are shown in Fig. 8.

This loop runs every five minutes while the microgrid is operating. In this paper, apart from the implementation of multiagent system, some of the best practices in computational intelligence (CI) techniques are also employed in decision making modules of the agents. For example, a Genetic Algorithm (GA) [28] was developed in the decision making module of the DSM Agent.

V. SIMULATION STUDIES AND RESULTS

Simulation studies were carried out on a 750 kW residential microgrid. The microgrid contains a photovoltaic (PV) system, a fuel cell (FC), three distributed generators (DG) (i.e., two microturbines (MT) and a diesel engine) and a battery bank. Details of these sources are given in Table I.

The electrical network of the microgrid was modeled in RTDS, which is shown in Fig. 9. The whole microgrid is operated at 410 V. Maximum power transfer capability of the interconnection link between the main grid and the microgrid is 100 kVA. Simulation studies were carried out for a typical day. Photovoltaic power production is calculated from the model given in RTDS library.

Perfect forecasting of solar radiation, atmospheric temperature, wind speed, and load were considered for the simulation. Hourly wholesale energy prices and load profile of the microgrid are given in Table II.

Battery bank has an initial charge of 75%. The load contains 75% of critical loads and 25% of noncritical loads at all the times. Both critical and noncritical loads are modeled as lumped loads in RTDS. The individual devices are not modeled separately. Noncritical load contains several types of controllable devices. The various device types in the microgrid and their consumption patterns are given in Table III.

There are over 2600 controllable devices available in the microgrid from 14 different types of devices. It is observed that demand side management agent has managed to bring the final consumption closer to the objective load curve. The simulation results obtained from load shifting by the DSM Agent are given in Fig. 10. The utility bills for the microgrid with and without

TABLE II
FORECASTED LOAD AND WHOLESALE ENERGY PRICES

Hour	Load (kWh)	Price (ct/kWh)	Hour	Load (kWh)	Price (ct/kWh)
1	457.7	8.65	13	345.2	26.82
2	336.5	8.11	14	320.6	27.35
3	274.9	8.25	15	333.2	13.81
4	272.6	8.10	16	316.8	17.31
5	245.3	8.14	17	291.3	16.42
6	233.7	8.13	18	413.8	9.83
7	274.6	8.34	19	539.8	8.63
8	291.0	9.35	20	557.2	8.87
9	315.7	12.0	21	557.1	8.35
10	362.4	9.19	22	535.0	16.44
11	320.0	12.3	23	437.8	16.19
12	350.0	20.7	24	447.3	8.87

TABLE III
DATA OF CONTROLLABLE DEVICES IN THE MICROGRID

Device Type	Consumption Pattern (kW)			Number of Devices
	1st Hour	2nd Hour	3rd Hour	
Dryer	1.2	-	-	189
Dish Washer	0.7	-	-	288
Washing Machine	0.5	0.4	-	268
Oven	1.3	-	-	279
Iron	1.0	-	-	340
Vacuum Cleaner	0.4	-	-	158
Fan	0.20	0.20	0.20	288
Kettle	2.0	-	-	406
Toaster	0.9	-	-	48
Rice-Cooker	0.85	-	-	59
Hair Dryer	1.5	-	-	58
Blender	0.3	-	-	66
Frying Pan	1.1	-	-	101
Coffee Maker	0.8	-	-	56
Total No of Devices	-	-	-	2604

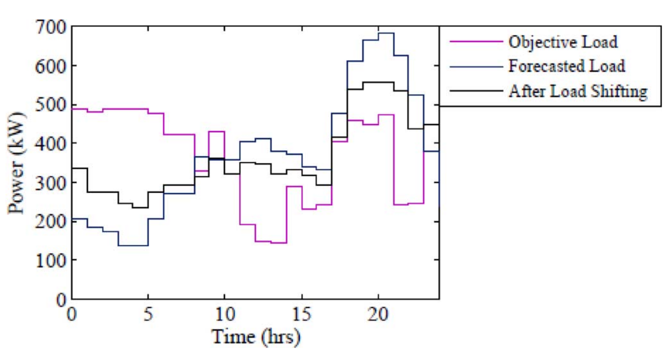

Fig. 10. Load profile of after load shifting by DSM agent.

load shifting are $1151.45 and $1094.15 respectively. Therefore, there is about 5.0% reduction in the operational cost by load shifting.

Results of generation scheduling of the microgrid in grid-connected mode are given in Fig. 11 and Fig. 12.

Fig. 11 shows the outcome of day-ahead scheduling of the grid-connected microgrid for the day. The microgrid receives power from the main grid from 18 h to 22 h, and supplies power to the main grid during remaining hours of the day. The power exchange between the main gird and the microgrid is at its maximum of 100 kW from 1 h to 17 h, but the power from the DGs

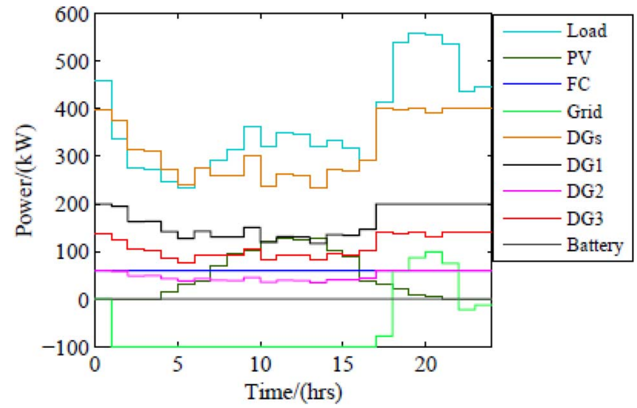

Fig. 11. Day-ahead hourly schedule of DERs in grid-connected microgrid.

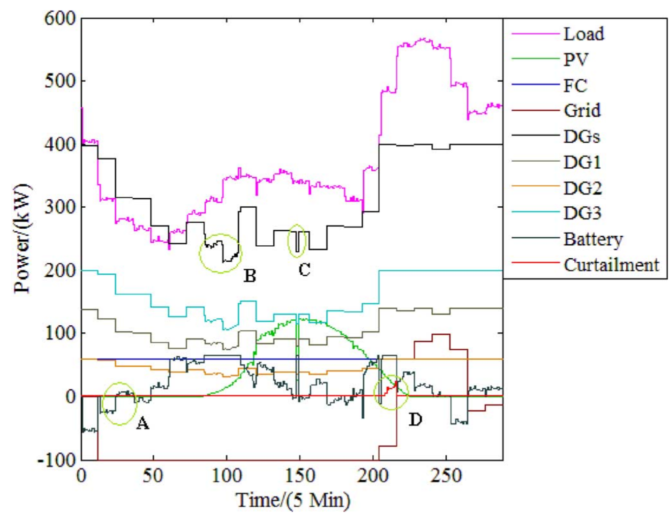

Fig. 12. Real-time scheduling of DERs in grid-connected microgrid.

are not at their maximum levels for the wholesale energy prices at the period. Therefore, it is possible to supply even more power to the main grid if the power transfer capacity of the interconnection link is increased.

Fig. 12 shows outcome of real-time scheduling of the grid-connected microgrid for the day. The results show that the real-time scheduling works as proposed, and maintains the stability of the microgrid. Four different situations can be clearly noticed in this figure. First, point A, it is a typical situation in real-time operation. As proposed, the load fluctuation is satisfactorily managed by the storage agent. Then, point B, when the load fluctuation goes beyond the capacity of storage agent, it is satisfied by the available DGs for the market price on time. Then, point C shows a situation when photovoltaic power drops due to some unexpected reasons such as cloud or shadow. In this case, it is managed by storage agent and DG Agents. Finally, point D, when the load fluctuation goes beyond the capacity of both storage agent and DG Agents, the microgrid has no other option but to call DSM Agent to do load curtailment or load shedding. In this case, DSM Agent has done some load curtailment, as seen from the figure.

Results of generation scheduling of the microgrid in islanded mode are given in Figs. 13 and 14. Fig. 13 shows outcome of day-ahead scheduling of the islanded microgrid for the day. The microgrid effectively manages serves its internal load from its sources except during the peak demand period from 19 h to 22

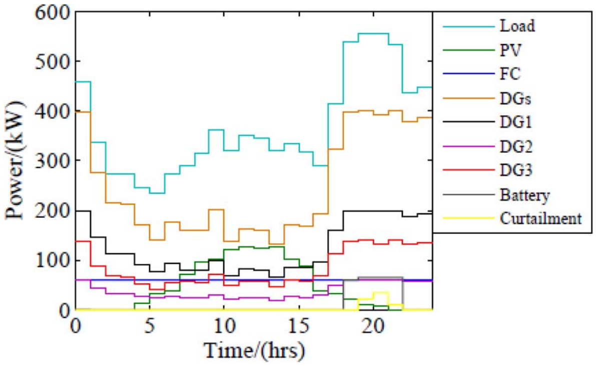

Fig. 13. Day-ahead hourly schedule of DERs in islanded microgrid.

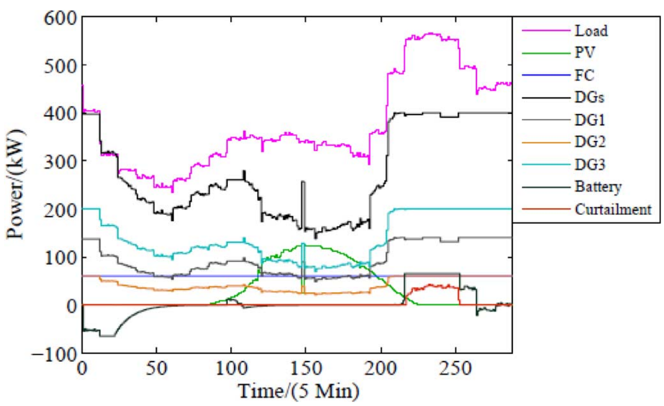

Fig. 14. Real-time scheduling of DERs in islanded microgrid.

h. During this period, DSM Agent carries out some load curtailment.

Fig. 14 shows outcome of real-time scheduling of the islanded microgrid for the day. The results show clearly that the real-time scheduling works as proposed, and maintains the stability of the microgrid even in the islanded mode. The four situations as explained above for Fig. 12 can also be seen clearly in the case of islanded operation.

VI. Conclusion

This paper presents a multiagent system for real-time operation of a residential microgrid in both grid-connected and islanded modes with a RTDS. The multiagent system was developed in an open source IEEE FIPA compliant platform, and a two-stage operational strategy was implemented on the multiagent system. The outcome of the simulation studies demonstrates the effectiveness of the proposed control and management technique, and shows the possibility of autonomous built-in operation of a microgrid with a multiagent system. The two stage scheduling described in the paper appears to be a useful tool for efficient management of a microgrid. The simulation studies have shown that the operational strategy is able to tackle both economical and technical objectives of the operation. Further developments of the scheduler will be investigated for control and management of large scale distribution networks in future, which will lead toward actual smart grid development.

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